CLIMATE OF THE SONORAN DESERT REGION*

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T HE desert nature of the lowlands peripheral to the Gulf of California first became known to the "outside" world shortly after the return of the ill-fated expedition commanded by Melchior Diaz, in 1540–41.[1] Clear qualitative descriptions of climates in this general area are scattered through more than 30 volumes of the "Documentos Para La Historia de Mexico," good examples being contained in the report of Cristobal de Canas (?), written in 1730,[2] and in the anonymous *Rudo Ensayo*, dating from about 1763.[3]

Numerous environmental studies in this general area have augmented our

[1] Winship, G. P., *The Journey of Coronado*, New York, 1922, pp. 26–30, 58–60.

Ives, R. L., "Melchior Diaz: The Forgotten Explorer," *Hisp. Amer. Hist. Rev.* XVI, 1936, 86–90.

[2] Ives, R. L. (Trans.), "The Sonoran Census of 1730," *Annals. Amer. Cath. Hist. Soc.* in press.

[3] Guitéras, Eusebio (Trans.), "Rudo Ensayo," *Records. Amer. Cath. Hist. Soc.* V, 1894, 137–140, et. seq.

knowledge of regional climate and climatic mechanics considerably.[4]   Listed works comprise less than one percent of the published information on the climate of this region: Large accumulations of unpublished data are on file at the University of Arizona and at the Desert Botanical Laboratory, both in Tucson, Arizona.

Within the last two decades, the climate of California has been investigated in considerable detail by Russell[5]; studies of rainfall in the Arizona and Sonora desert regions continued by Sykes (and others); and the climates of Mexico outlined by Contreras Arias.[6]   The official weather services of the United States and Mexico have collected a vast amount of dependable weather data during the last 40 years. Much of this has been published in their serial data sheets and summaries:[7] the remainder, with practically no exceptions, is available at the regional offices of the services concerned.

Material here to be presented is a summary of the foregoing information, augmented and checked by data collected in the field during the period 1928–1947, inclusive.   Field studies included several thousand miles of traverses of the desert areas of Arizona, Sonora, and Baja California, afoot; about an equal mileage of jeep traverses; and more than two hundred hours of aerial reconnaissance.

[4] Bryan, Kirk, *The Papago Country, Arizona: A Geographic, Geologic, and Hydrologic Reconnaissance, with a Giude to Desert Watering Places*, U. S. Geol. Survey Water Supply Paper 499, Washington, 1925, p. 79 et. seq.

Davis, W. M., "Sheetfloods and Streamfloods," *Bull. Geol. Soc. Amer.* XLIX, 1938, pp. 1337–1416.

Gilluly, James, "Physiography of the Ajo Region, Arizona," *Bull. Geol. Soc. Amer.* XLVIII, 1937, pp. 323–348.

Ives, R. L., "Desert Floods in the Sonoita Valley," *Amer. Jour. Sci.* XXXII, 1936, pp. 349–360.

Lumholtz, Carl, *New Trails in Mexico*, New York, 1912, p. 16 et. seq.

McGee, W. J., "Sheetflood Erosion," *Bull. Geol. Soc. Amer.* VIII, 1897, pp. 87–112.

Shreve, Forrest, "Rainfall, Runoff, and Soil Moisture Under Desert Conditions," *Annals. Assn. Amer. Geographers*, XXIV, 1934, 131–156.

Sykes, Godfrey, "Rainfall Investigations in Arizona and Sonora by Means of Long-Period Rain Gauges," *Geog. Rev.* XXI, 1931, pp. 229–233.

[5] Russell, R. J., "Climates of California," *Univ. Calif. Pubs. in Geog.* II, 1926, pp. 73–94 et seq.: "The Dry Climates of the United States," *ibid*, V, 1931, pp. 1–41.

Leighly, John, "Graphic Studies in Climatology," *Univ. Calif. Pubs. in Geog.*, II, 1926, pp. 55–71.

[6] Contreras Arias, Alfonso, *Mapa de las Provincias Climatologicas de la Republica Mexicana*, Mexico. D. F., 1942.

[7] United States Weather Bureau, *Climatological Data*, monthly and annual, by areas (usually states), Washington.

United States Department of Agriculture, *Climate and Man, Yearbook of Agriculture, 1941*, Washington, 1941.

Servicio Meteorologico Mexicano, *Boletin Anual del Servicio Meteorologico Mexicano*, annual (with some numbers not published), Tacubaya, D. F.

Contreras Arias, Alfonso, *op. cit.*

GEOGRAPHICAL SUMMARY

Location

The geographical region containing the Sonoran Desert, as well as several other climatic regimes, is normally bounded by Latitudes 20° and 38° North; and Longitudes 104° and 121° West. This area (Fig. 1) includes all parts or the states of California, Nevada, Utah, Colorado, Arizona, New Mexico and Texas, in the United States; the territory of Baja California, and all or parts of the states of Sonora, Chihuahua, Sinaloa, Durango, Nayarit and Jalisco, in Mexico. The best detailed maps of the area as a whole are those comprising the World Aeronautical Chart.[8] Detailed maps of small parts of this area have been published by the U. S. Geological Survey, and by various Mexican agencies.

Sea areas in this general region, and details of the offshore islands in the Pacific and in the Gulf of California, are shown with considerable accuracy in the appropriate "Coast Pilot."[9]

Topographic Summary

Major topographic features of this region consist, from west to east, of a narrow coastal flatland, bordering on the Pacific (Fig. 1), with a width of from zero to about thirty miles. This grades into a piedmont area, narrow in most places, composed in large part of alluvium, but consisting in some places of fairly typical pedimental structures.

A few miles inland, and rising to heights exceeding 11,000 feet in a few places, is a major mountain barrier, consisting of the Sierras in California, and of the Peninsular Ranges in Baja California. Average height of the peninsula "backbone", which is subdivided into the Sierra Juarez, the Sierra de San Pedro Martyr, the Sierra San Lino, Sierra de Santa Lucia, Sierra de La Giganta, and the Sierra San Lazaro, decreases southward, toward the tip of the peninsula. Ancient shorelines, a few miles north of La Paz (Fig. 1), indicate that, during Pleistocene highwater stages, the Sierra San Lazaro was an island some miles offshore, and that the end of the peninsula was the southern face of the Sierra de la Giganta.

East of the Sierras and Peninsular Ranges, extending southward at least to Mazatlan (Fig. 1) from the Nevada-California line at about Latitude 38° N., is the California Rift, a fault-bounded topographic depression which contains the Gulf of California in its southern part, and two dry depressions—the Salton Sink and Death Valley—which are considerably below sea level. The Salton Sink, now an irrigated area, is today known as the Imperial Valley, and contains the Salton Sea, maintained by the subdrainage of the irrigated lands at higher levels. Death Valley,

[8] *World Aeronautical Chart*, 1/1,000,000, U. S. Coast and Geodetic Survey, Washington, D. C.: regular revisions. Area concerned is covered by sheets:—(AAF Code designations, Code APC-1) #404 *Mojave Desert*, #405 *Gila River*, #406 *Estacado Plain*, #470 *Santiago Mountains*, #471 *Sonora River*, #472 *Sierra San Pedro Martyr*, #520 *Giganta Range*, #521 *Lake Santiaguillo*, #591 *Cabo San Lucas*, and #590 *Lake Chapala*.

[9] H. O. No. 84, *Sailing Directions for the West Coasts of Mexico and Central America*, U. S. Hydrographic Office, Washington, D. C., 1937.
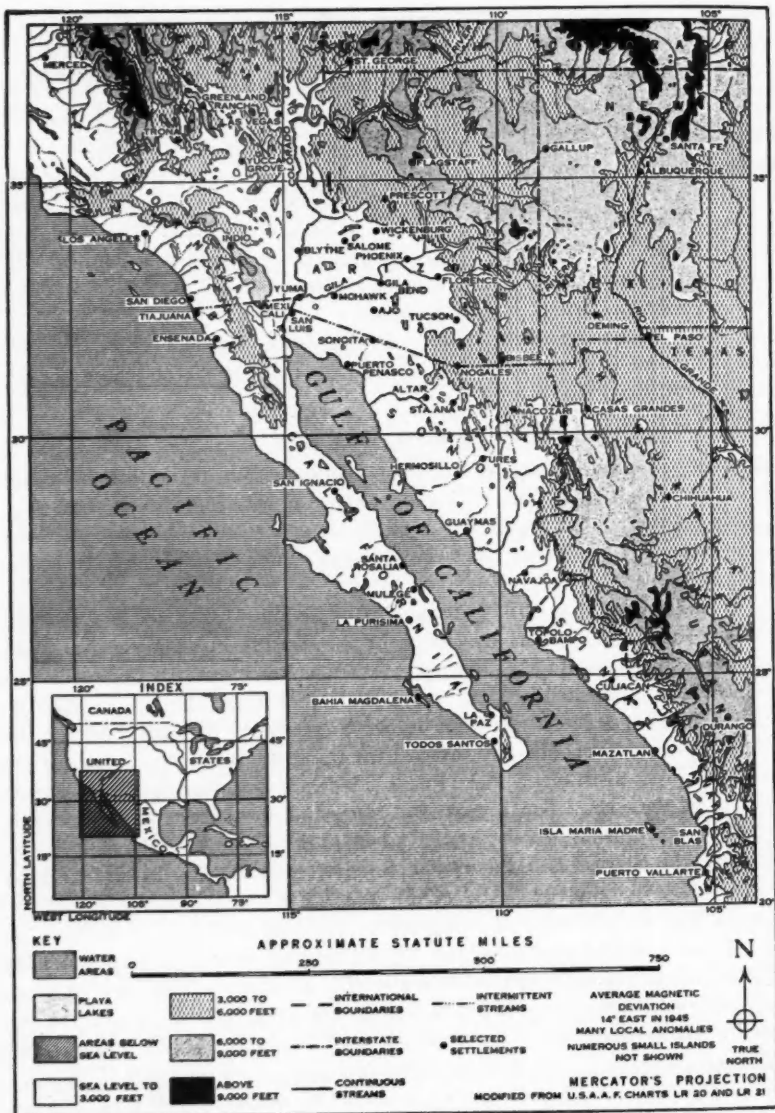
FIG. 1. Summary map of the southwestern part of the United States and northwestern Mexico, showing major terrain features, important hydrography, larger political divisions, and locations of selected meteorological stations.

the site of Greenland Ranch, traditionally "twenty miles from wood, twenty miles from water, forty feet from Hell," is occupied by a salt bed, about 280 feet below mean sea level.   Maximum width of the California Rift is slightly greater than 100 miles.

On the east of the California Rift is a complex mass of fault-block mountains and depressions, having a north-northwesterly trend.   These are the southern outliers of the Basin-and-Range physiographic province[10], which terminates northeastward against the Colorado Plateaus, and southeastward against the Sierra Madre Occidental of Mexico, leaving a low gap, extending east and west, between the Gila River and the U. S.—Mexican border, which is an important highway and railroad pass from the Rio Grande Valley to the Colorado Valley.

Small parts of the Southern Rocky Mountains are shown in the northeastern corner of Figure 1; and a fragment of the Bolson de Mapimi is included in the southeast.

Land forms in the map area (Fig. 1) are those typical of arid and semi-arid fault-block-mountain and plateau areas.   Their appearance and probable mode of origin are outlined in any standard work on geomorphology, such as Worcester[11]. Geological and topographic features pertinent to regional and local climate will be outlined where appropriate.

Hydrography

Although the land area here mapped extends over about 1,000,000 square miles, it contains only two large perennial rivers—the Colorado and the Rio Grande —and both originate in mountain areas where climatic conditions are decidedly not desert.   The Gila, major tributary of the Colorado, which also originates in a highland area, has become an intermittent stream within historic times.

Flows of all major streams in this area—both perennial and intermittent—in both the United States and Mexico have been altered greatly in recent years by diversions for irrigation purposes.

Although underground water is known to be present in more than half of the map area (Fig. 1) at depths of less than 300 feet, much of it is not only stationary, but is so loaded with chemicals (largely soluble salts) that its biological utility is greatly impaired.   Many desert aquifers have been depleted, or have "gone saline," in recent years, because of pumpage at rates very greatly exceeding recharge.

Vulcanism and Seismicity

The entire map area is a region of geologically recent volcanic activity, much of it during the Pleistocene.   A moderate volcanic outbreak occurred in many parts of the region since the coming of man to North America, and the latest eruptive disturbances probably took place not more than 1,000 years ago.

In consequence of this regionally quiescent vulcanism, there are numerous hot

[10] Fenneman, N. M. *Physiography of the Western United States*, New York, 1931, pp. 326–395.

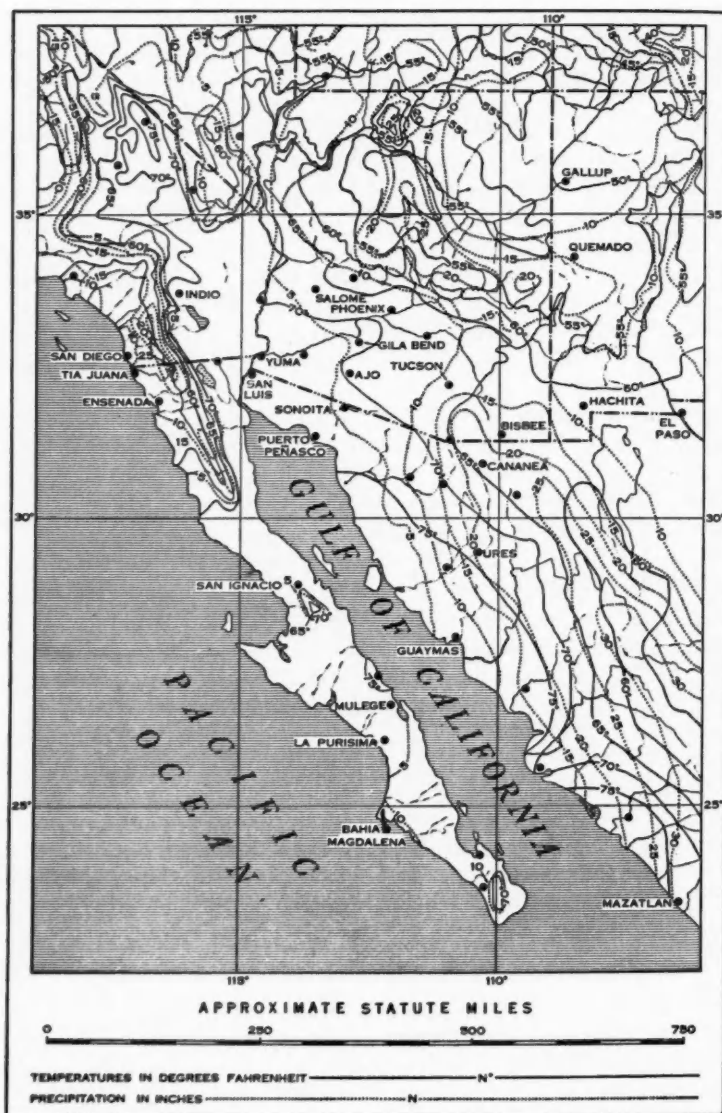[11] Worcester, P. G. *Textbook on Geomorphology*, New York, 1949, pp. 220–263.

Fig. 2.   Mean annual temperatures and rainfalls in the Sonoran Desert and adjacent regions.
Data from official weather services of the United States and Mexico.

springs in the area, particularly near the more recently active volcanoes; and mud volcanoes are found on the west side of the California Rift, particularly at Volcano Lake, Baja California, where they were first observed in 1540.[12]   Vague reports ("millions" of dead fish after earthquakes; "stones that floated") suggest minor submarine volcanic outbreaks in the Gulf of California during the last three decades.

Trending roughly from northwest to southeast, from the west side of the California Sierras to central Arizona, are a number of active faults.   Relief of accumulated stresses along these takes place frequently, producing numerous earthquakes, most (but not all) of which are of little importance.   A number of recent studies of microseisms[13] suggest a relation between barometric fluctuations and minor earthquakes, but for the area concerned, the exact relationship has not been demonstrated conclusively.   A further investigation, to evaluate the possible "trigger" effect of violent barometric disturbances, such as tropical cyclones, on stressed fault zones, seems to be in order.

PRELIMINARY CLIMATIC PLOTTING

From the summaries published by the U. S. Weather Bureau and by the Servicio Meteorologico Mexicano, a chart showing the mean annual temperatures and the mean annual rainfalls in the map area (Fig. 1) can be drawn.   With present knowledge, such a chart, which comprises Figure 2, does not involve any large extrapolations, and, as normally drawn, is in close accord with climatic inferences drawn from vegetation distribution and erosion types.

A chart of this type, however, even though it presents a large part of the desired data, is quite difficult to interpret, and more difficult to translate into a usable climatic chart.   In addition, climatic definition by use of annual values only conceals the temperature—precipitation phase relations, which, in many instances, are biologically more important than the actual magnitudes (see Appendix A for description of phase relations).   Choice of a climatic system, which not only presents the desired information in usable form, but which neither conceals information of possible value nor entails great amounts of awkward computations, is needed in this study.

CLIMATIC SYSTEMS

Of the three systems of climatic designation now in common use, the original Köppen system[14], although the best known, is probably least suited for application to western American climates.

Similar to Köppen's classification, but somewhat improved, from the viewpoint of the North American climatologist, is Trewartha's system, which corrects many

[12] Winship, G. P. *The Journey of Coronado*, New York, 1904, pp. 58–59.

Sykes, Godfrey, *The Colorado Delta*, Washington, 1937, pp. 9–10, Fig. 29.

[13] Press, Frank; and Ewing, Maurice, "A Theory of Microseisms with Geologic Applications," *Trans. Amer. Geophys. Union*, XXIX, 1948, 163–174.

[14] Köppen, Wladimir, "Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt," *Geogr. Zeitschr.* VI, 1900, 593–611, 657–679.   Modified classification in Köppen-Geiger, *Klimatkarte der Erde*, Gotha, 1928.

of the defects of the original Köppen classification[15], and supplies a workable system which is comprehensible to the average investigator of the earth sciences.

About two decades ago, as a result of studies of the relations between precipitation, evaporation, and temperature, C. W. Thornthwaite developed a third system of climatic classification which merits careful consideration.[16]   In this system, the elements *temperature* and *precipitation* are replaced by *temperature efficiency* and *precipitation effectiveness.*

Parallelling and augmenting the study which led to the establishment of the foregoing climatic systems are the studies by Emmanuel De Martonne and his co-workers,[17] in which relations of rainfall and evaporation to runoff pattern were investigated.   From these studies was developed a most useful climatic constant—the index of aridity,[18] a modification of Lang's rain factor.[19, 20]   Because it is based solely on annual values, which become stable in a much shorter time than monthly values, the index of aridity is quite useful in areas where long-term climatic records are not available, as is the case in the area concerned.   Similarly, it is useful in areas of capricious rainfall, such as the American southwest and the Mexican northwest, where an appreciable part of a year's rainfall may occur in one afternoon.

Because it is based solely on annual values, the index of aridity is not an entirely satisfactory climatic indicator, when used alone, for, by its use, a dry tropical savanna area (summer rainfall maximum) will be shown climatically the same as moist Mediterranean area (winter rainfall maximum) having the same mean annual rainfall and mean annual temperature.   From either a cultural or biotic standpoint, these areas do not have the same climate.

If, in combination with the index of aridity, the relation of rainfall maximum to temperature maximum is also stated (phase relationship, Appendix A), the foregoing objections are eliminated, and climatic classifications can be made systema-

[15] Trewartha, G. T. *An Introduction to Weather and Climate*, New York, 1943, pp. 309–315, et seq.

[16] Thornthwaite, C. W., "The Climates of North America According to a New Classification," *Geog. Rev.*, XXI, 1931, pp. 633–655 : "The Climates of the Earth," *Geog. Rev.*, XXIII, 1933, pp. 433–440 : "Problems in the Classification of Climates," *Geog. Rev.*, XXXIII, 1943, pp. 232–255.

[17] De Martonne, Emmanuel, "Aréisme et indice d'artidité," *Comptes Rendus de L'Academie des Sci. de Paris*, CLXXXII, 1926, pp. 1395–1398 : "Regions of Interior-Basin Drainage," *Geog. Rev.*, XVII, 1927, pp. 397–414.

[18] This index is computed from :—

$$I_{ar} = \frac{P}{T + 10}$$ in which P = precipitation in millimeters and   T = Temperature in degrees C.

or :—

$$I_{ar} = \frac{45.72\,P}{T - 14}$$ in which P = precipitation in inches and   T = Temperature in degrees F.

[19] Lang, Richard, *Verwitterung und Bodenbildung als Einfuhrung in die Bodenkunde*, Stuttgart, 1920, pp. 107–123.

[20] Some elaboration of the formula :—

$$I_{ar} = \frac{f(P)}{f(T)}$$ in which P = precipitation in millimeters and   T = Temperature in degrees absolute

offers some hope of correlating climatic computations and methods with those of physical chemistry.
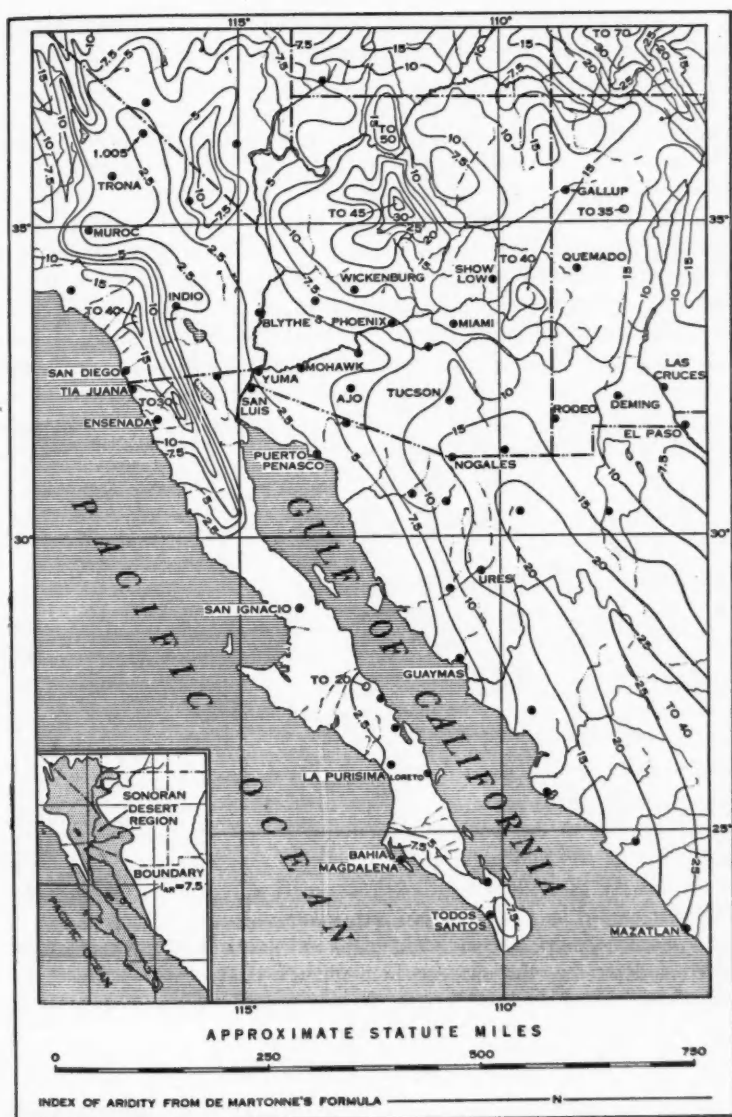
FIG. 3.   Indices of aridity, as computed by De Martonne's formula, for the Sonoran Desert and surrounding regions.

tically, so that all workers using the same data arrive at the same classification, without the use of involved computations or abstruse theories.

AREAL INDICES OF ARIDITY

Indices of aridity for pertinent parts of the main map area (Fig. 1), as computed by De Martonne's formula (Note 18), from official weather observations, augmented by field data, are shown in Figure 3. The boundary of the Sonoran Desert, as the term is here used, is set a $I_{ar} = 7.5$, a value in substantial accord with much biotic evidence; and the extent of the Sonoran Desert, thus defined, is shown in the inset (lower left) of Fig. 3. Although the boundary is drawn as a line, it is actually a band of very gradual transition, which not only shifts seasonally and annually, but which, in most parts of the area concerned, may be located erroneously by as much as five miles, due solely to the unavoidable "rounding off" error inherent in meteorological observations. Inclusion of many other errors, due to wide spacing
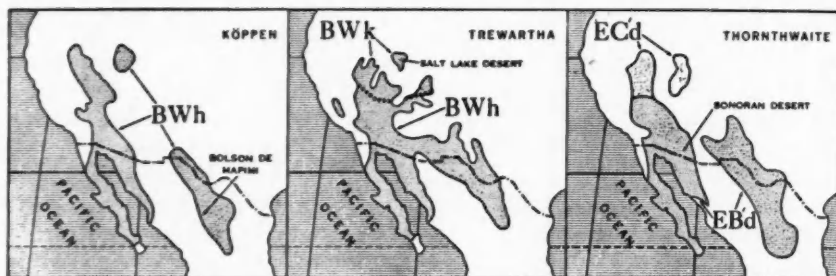
Fig. 4. Desert areas of the southwestern United States and Northwestern Mexico as defined by various climatic systems.

of meteorological stations, short duration of records, and the capricious rainfall of the region, is probable.

During a series of dry years, the Sonoran Desert expands, joining with the deserts of Nevada and Chihuahua, and sometimes also with the Salt Lake Desert. In wet periods the Sonoran Desert contracts markedly, leaving many small desert enclaves, surrounded by newly-created steppe lands.

The Sonoran Desert, as here defined, is substantially coextensive with areas designated as desert by other systems in common use, as is demonstrated in Figure 4. The similarities of the final results, despite the differences in methods, criteria, and basic data employed, are rather striking.

REGIONAL RAINFALL DISTRIBUTION

Although the entire area outlined (in Fig. 3, inset) is a desert according to any ordinary method of climatic designation, conditions within the desert are by no means uniform. Not only is the rainfall extremely variable from year to year, as is shown by the Yuma rainfall record (Fig. 5), but the rainfall distribution is areally erratic and seasonal distribution of rainfall is not everywhere the same. Along a

section from the west coast of Baja California to the Arizona uplands (Fig. 6), rainfall distribution varies from winter maximum (180° out of phase with temperature), characteristic of Mediterranean shores; to summer maximum (rainfall and temperature substantially in phase), having weak monsoon characteristics.

A part, but only a part, of this areal and seasonal variation can be attributed to

FIG. 5. Monthly and annual rainfall totals for Yuma, Arizona, for the period 1925–1945, demonstrating extreme variability of monthly totals, the great, but comparatively smaller, variability of annual values.

direct terrain effects, such as rain shadows. During the winter season, when extensive air motion from the Pacific across the peninsular mountains takes place, the absence of rain in the California Rift area can be attributed to rain-shadowing. However, during the summer season, when less air crosses the peninsular ranges, and this air is relatively dry at low levels, the rain shadow does not operate.

Squall zones, the result of localized concentration of the convective updrafts of large areas, are present over the northern peninsular ranges, and over the Mogollon rim, as might be predicted from a consideration of standard climatic mechanics. To these squall mechanisms may be attributed the intensely violent, but short-lived, hailstorms of the Mogollon region, notably in the vicinity of Show Low (Fig. 4) and McNary (Arizona). Strong vertical air currents are the rule here, during the summer season, even in clear weather. A flight from Lordsburg (N. M.) to Winslow (Ariz.), in a light plane, on almost any clear summer day, will demonstrate these effectively to the most sceptical.
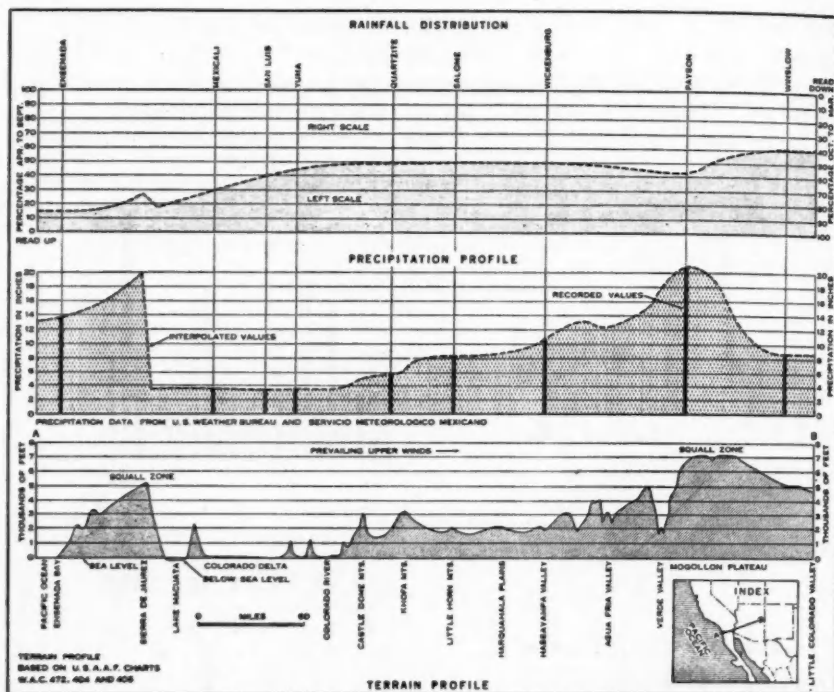
FIG. 6. Profile from the west coast of Baja California to the uplands of central Arizona, showing terrain profile (A—B), rainfall profile (center), and seasonal distribution of rainfall (top).

The squall zone over the peninsular ranges of Baja California is somewhat complicated by the presence of the potentially frontogenetic situation, shown diagrammatically, for a typical case, in Figure 7. Here, air, from the Pacific, containing considerable moisture is heated (to T_{01}), and rises convectively on the western side of the peninsular ranges. From the surface to the height of condensation (H_c), this air cools at the dry adiabatic rate: above the height of condensation, this air cools at a considerably lesser rate, and is saturated, normally producing rainfall.

On the opposite (eastern) side of the mountains, desert air, having a lower relative humidity, is also heated (to T_{02}), and rises convectively, cooling at the dry adiabatic rate until *its* height of condensation (above the upper margin of Fig. 7) is reached; then cooling at a lesser rate. Whenever the temperatures of the two convective updrafts are different, as is usually the case, a local, weak, and commonly stationary, front develops over the peninsular ranges. This, if biased laterally by eastward air motion, has many of the characteristics of a warm front.
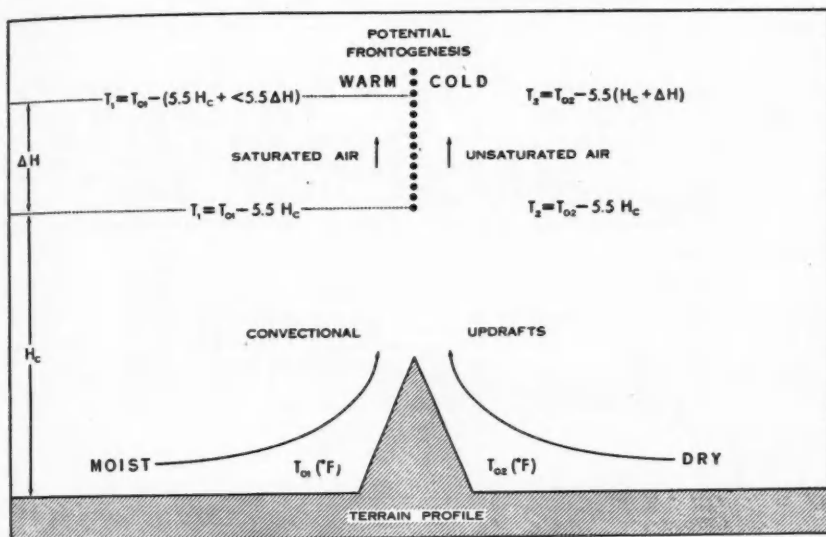
POTENTIAL
FRONTOGENESIS

WARM · COLD

$T_1 = T_{o1} - (5.5 H_c + <5.5 \Delta H)$ $T_2 = T_{o2} - 5.5(H_c + \Delta H)$

ΔH

SATURATED AIR ↑   ↑ UNSATURATED AIR

$T_1 = T_{o1} - 5.5 H_c$ $T_2 = T_{o2} - 5.5 H_c$

H_c

CONVECTIONAL   UPDRAFTS

MOIST T_{o1} (°F) T_{o2} (°F)   DRY

TERRAIN PROFILE

FIG. 7. Potential frontogenesis over the "backbone" of Baja California, produced when air masses of differing characteristics meet.

In general, fronts produced over the peninsular ranges are relatively minor, but they appear to be a causative factor in the generation of migratory families of squalls which, originating in the Sierra San Pedro Martyr (or its vicinity), sweep north-eastward across the basin and range region to such points as Fort Bridger, Wyoming, and Pocatello, Idaho[21], bringing intensely violent storms to a relatively narrow trajectory. Because of lack of meteorological stations within the probable source area, sparse population along much of the squall trajectory, and the many possible combinations of meteorological factors in this area, forecasting of these squalls is difficult; further study of them may be productive.

Similar potentially frontogenetic conditions exist, at least theoretically, over any mountain range, but few fronts so produced are of more than local importance due in large part to the small magnitude of the produced air-mass difference.

When longitudinal rainfall profiles of the area are considered, the rainfall variations, although still great, are found to be a series of fairly gradual transitions from north to south, with rainfall of the "Mediterranean" type[22] predominating in the northwest coastal areas, and being replaced by "monsoon" rainfall (summer

[21] Greenling, G. K. "Severe Hailstorm at Salt Lake City, Utah, August 19, 1945", *Miscell. Publ. Utah Min. Soc.*, 1945.

Ives, R. L. *Interrelations of Terrain, Climate, and Weather in the Southern Salt Lake Desert*, forthcoming.

[22] Called "summer dry" by Leighly, in *Climate and Man*, pp. 197–204.

FIG. 8. Topographic, rainfall, and rainfall distribution profiles for three sections roughly paralleling peninsular California.

rainfall maximum) inland and toward the south.[23]

Profile of actual amount of rainfall along three sections roughly paralleling the "backbone" of Baja California, diagrams showing the seasonal distribution of this rainfall, and a topographic profile of Baja California, comprise Figure 8.

Along the Pacific Coast (A—B, Fig 8), rainfall diminishes in amount from north of Los Angeles to the Vizcaino Desert of Baja California, then increases southward. In this area also, a rainfall phase change takes place, the pattern near Los Angeles being very definitely Mediterranean, whereas that to the south of the Vizcaino Desert is just as definitely "Monsoon" (summer maximum). Interestingly, the transition, according to available records, which are in close accord with biotic evidence, takes place in an area of minimum rainfall (about 3 inches annually).

The crest line of Baja California, summarized from the best maps available in 1948, is shown in section C—D (Fig. 8). Because the topographic crest is not necessarily the aerodynamic crest, a smoothed crest silhouette, based on a 50-mile progressive average of crest elevations, is also shown (Fig. 8, C—D, dotted crest line). This smoothed crest silhouette approximates the aerodynamic crest of the peninsula quite closely in some areas when air motion is normal to the projection plane, but is not as satisfactory for winds which impinge upon the plane at an acute angle. Lack of both geographic and meteorological data prevents construction of a better aerodynamic profile at present (1948).

Annual rainfall totals for the area east of the peninsular ranges and west of the California Rift are shown in section E—F (Fig. 8), with a rainfall distribution chart immediately above; and conditions of the east side of the California Rift are shown in the remaining two profiles (G—H, Fig. 8).

Rainfall magnitudes here are compatible with assumption of rain-shadow effects in the northern part of the area, particularly in winter; but indicate just as plainly that no such effects prevail in the southern part of the region. The southern parts of the "backbone" of Baja California do not receive the heavy rainfalls called for by orographic theory, and temperatures are quite similar, level for level, on both sides of the peninsular mountains. Notable also is the persistence of the winter rainfall maximum, in the northern part of the area, into the driest places in North America (such as Greenland Ranch, in Death Valley).

INDIVIDUAL STATION RECORDS

Although the areal and seasonal distributions of rainfall and temperature are shown in a general way in the foregoing illustrations, details of the changes in temperature—precipitation relations are more clearly shown by selected individual station records.

[23] This transition occurs along the entire west coast of North America, the variation being from February maximum at San Diego to October maximum along the Alaskan Coast (see Williams, Philip, Jr., "The Variation of the Time of Maximum Precipitation Along the West Coast of North America", *Bull. Amer. Met. Soc.*, XXIX, 1948, pp. 143-145); and to summer maximum at the southern tip of Baja California (see Fig. 8, this paper).
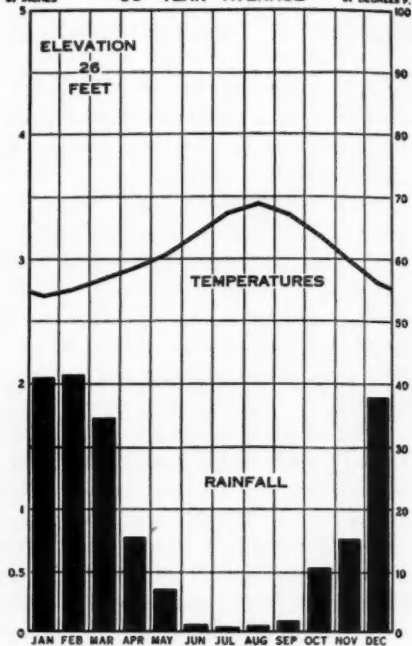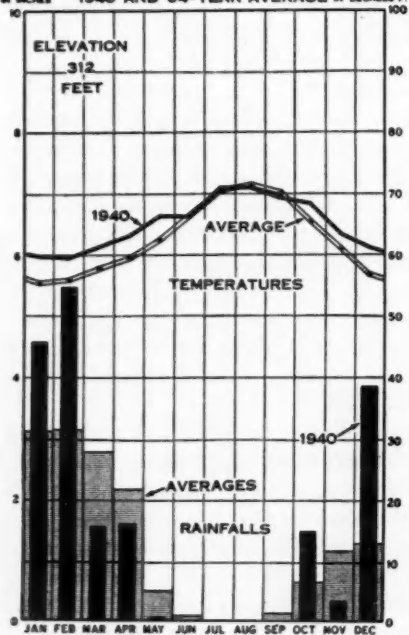
LOS ANGELES   CALIF.

PRECIPITATION IN INCHES   1940 AND 64-YEAR AVERAGE   TEMPERATURES IN DEGREES F.

ELEVATION 312 FEET

1940   AVERAGE   TEMPERATURES

1940   AVERAGES   RAINFALLS

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

SAN DIEGO   CALIFORNIA

PRECIPITATION IN INCHES   66 YEAR AVERAGE   TEMPERATURES IN DEGREES F.

ELEVATION 26 FEET

TEMPERATURES

RAINFALL

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

SAN IGNACIO   B. C.

PRECIPITATION IN INCHES   THREE YEAR AVERAGE   TEMPERATURES IN DEGREES F.

ELEVATION 1575 FEET

TEMPERATURES

RAINFALL

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

LA PURISIMA   B. C.

PRECIPITATION IN INCHES   THREE YEAR AVERAGE   TEMPERATURES IN DEGREES F.

ELEVATION 820 FEET

TEMPERATURES

RAINFALL

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
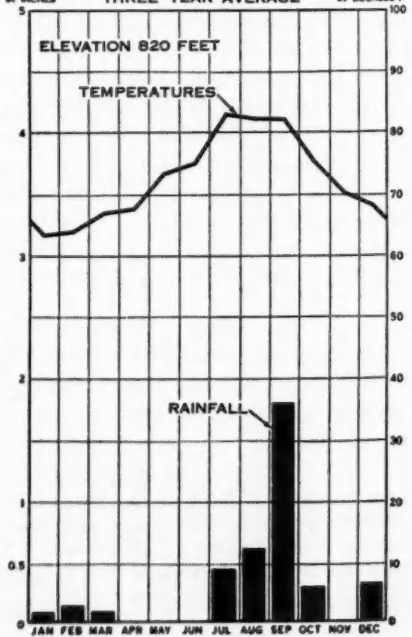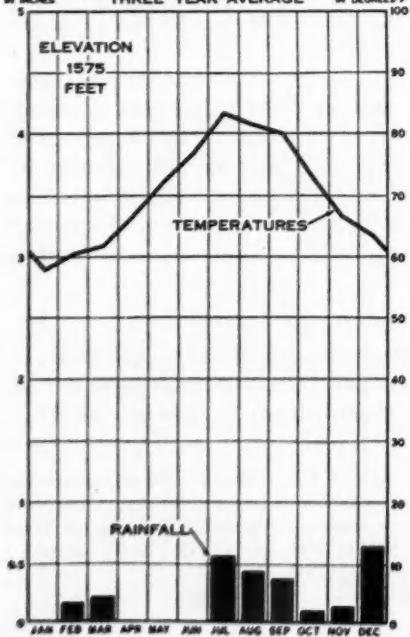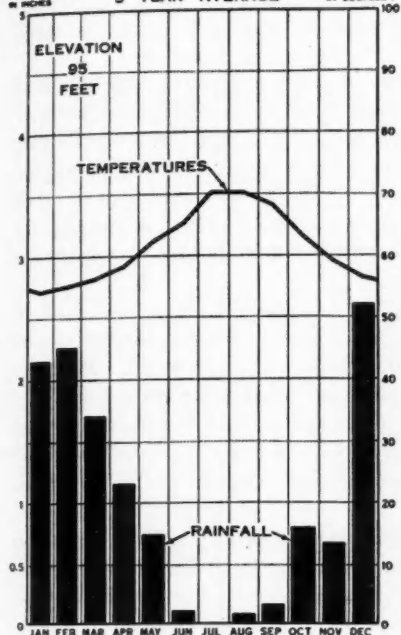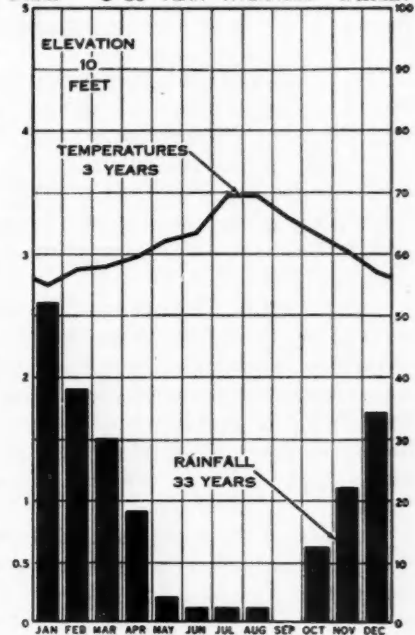
FIG. 9. Representative station summaries, by months, for the Pacific Coast from Los Angeles south to Todos Santos.
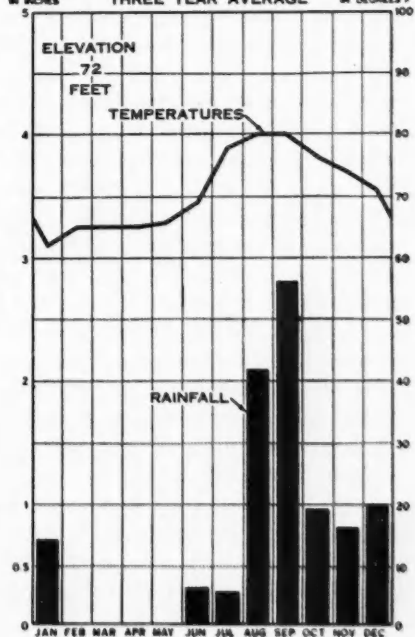
The sequence of charts from the Pacific coast stations, comprising Figure 9 shows a typical "Mediterranean" rainfall-temperature relation at Los Angeles, and a rather clear "Monsoon" chart at Todos Santos.   The charts from Baja California indicate quite plainly that the station averages have not yet stabilized.   It should be emphasized that the transition from Mediterranean to Monsoon rainfall type in Baja California is gradual; the apparent sudden change between Ensenada and San Ignacio is due to the wide spacing of the stations in that area and not to a sharp climatic boundary.

Inland, east of the peninsular "backbone", the country is much more arid, in general; yet the same transition from winter rainfall maximum to summer rainfall maximum continues, as is shown by the station diagrams in Figure 10.   Note that some of the southern stations have a composite, or "mixed" rainfall pattern, consisting of a weak Mediterranean curve, with a stronger Monsoon curve superposed. Because the Mexican official averages, in this series, cover records from more than ten years, the curves are smoother than those from the western side of Baja California.

Stations on the eastern side of the California rift show a gradual transition from the driest part of North America—Greenland Ranch, in Death Valley—to a very wet location, Mazatlan, a seaport on the northern margin of the Tierra Caliente of western Mexico, outside of the desert area.   Included in this sequence (Fig. 11) is a chart for Isla Maria Madre, Nayarit, principal island of the Mexican penal colony, which gives a fair indication of weather and climate in Pacific coastal waters. Here also is apparent a mixed rainfall pattern, with a weak mediterranean pattern (winter maximum) present at all stations; and a monsoon pattern (summer maximum) present toward the south, and increasing in magnitude southward.

Throughout this sequence of charts, the temperature of the hottest month increases northward, even though the mean annual temperature decreases in that direction.   In consequence, the mean annual temperature ranges increase northward at a great rate.   As will be detailed later, the summer dryness of most parts of the desert is a result, in part, of the northward increase in summer temperature, which produces lowered relative humidities northward, and inhibits convective rainfall.

Climate of the northeastern periphery of the Sonoran Desert area, where the rainfall pattern is modified not only by altitude, but also by rather complicated mixtures of rainfall regimes, is outlined by the station charts in Figure 12.   Here, in the various station summaries, can be seen precipitation patterns consisting of mixtures of Mediterranean, Monsoon, and "Snake River" (spring and fall maxima; winter and summer minima) regimes.   Because of locations of some of these stations with respect to changes in terrain elevation, they are on the "receiving" aspect with respect to some orographic rains; and "shadowed" with respect to other orographic precipitation.

From the Gila Valley of Arizona, southward to Ures, in the Rio de Sonora Valley, the Monsoon rainfall everywhere exceeds, in magnitude, the Mediterranean rainfall, but in no part of the area is the Mediterranean pattern completely lacking (Fig. 13), and in some records, a subdivision of the Mediterranean pattern is suggested.
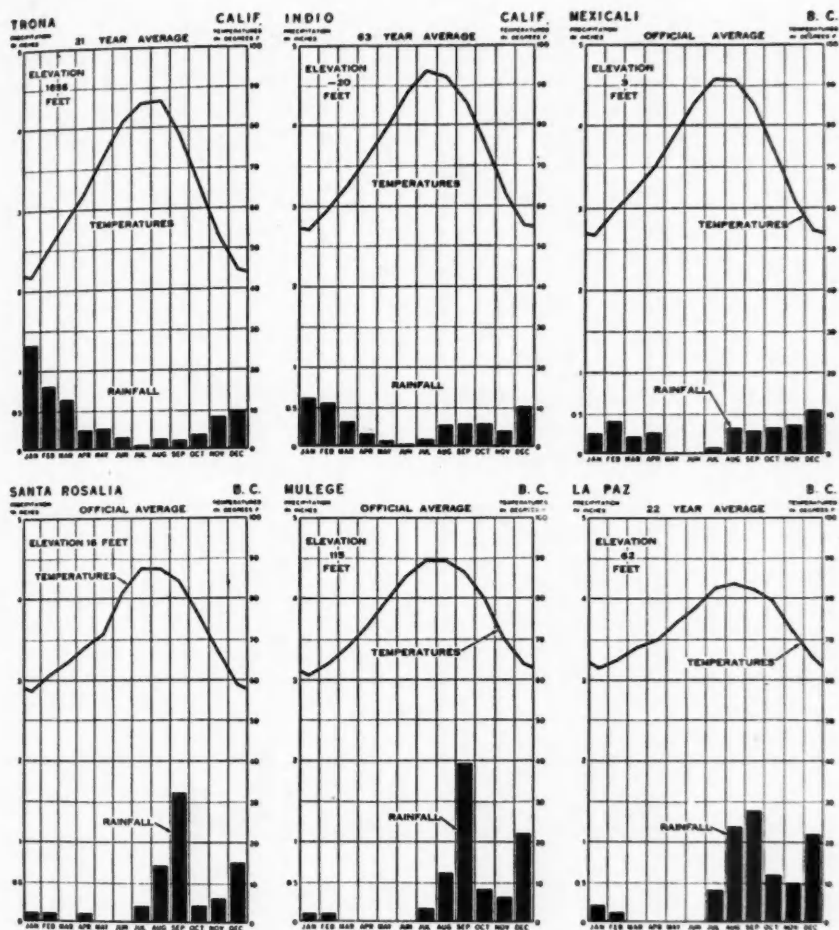
FIG. 10. Station charts for the western side of the California Rift, from Trona south to La Paz.

Rainfall and temperature regimes of the desert are not strictly confined to the desert, but extend, with some slight changes of magnitude, for a considerable distance beyond it. Only where the desert-steppe boundary coincides with a distinct topographic break is the boundary either sharp or fixed.

Within the boundaries of the desert area (Insert, Fig. 5), are a number of small areas where, because of elevation, usually aided by orographic effects, the index of aridity is numerically larger than 7.5; and exterior to the desert area, as defined,
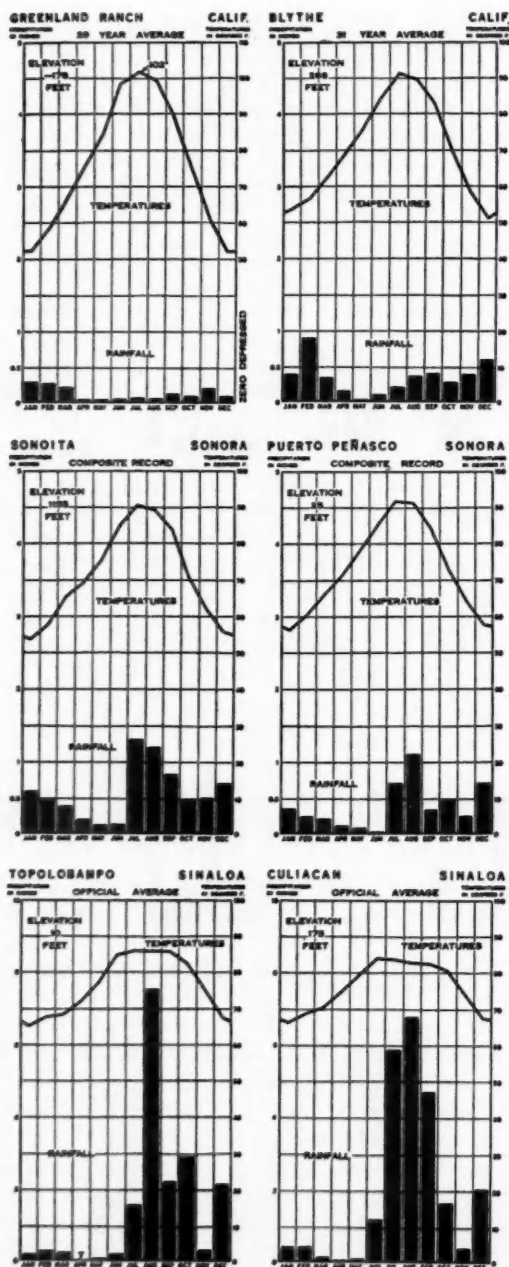
FIG. 11. Station charts for selected locations on the east side of the California Rift, from Greenland Ranch south to Mazatlan.
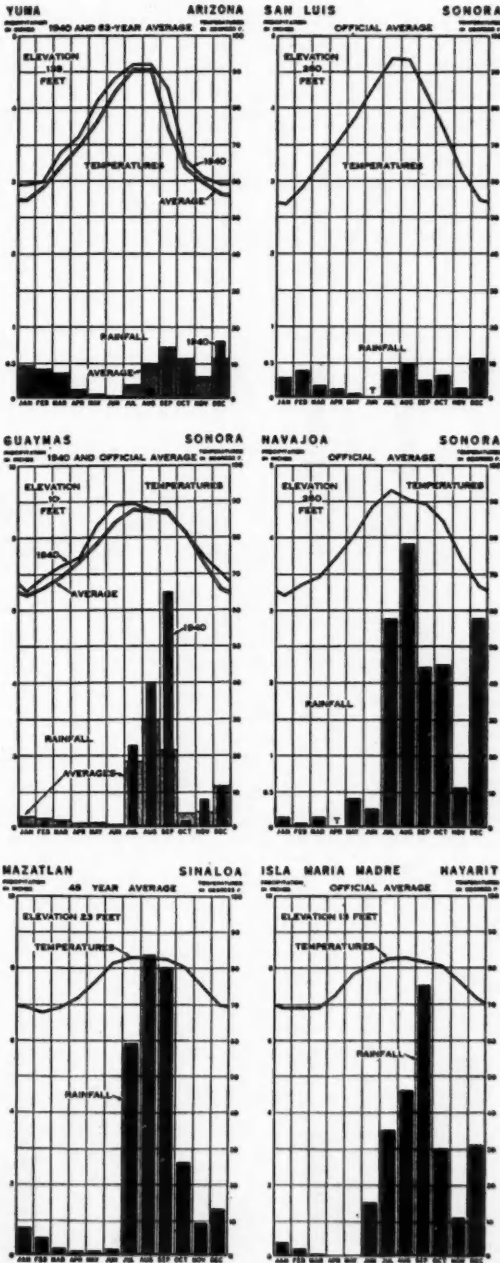
YUMA   ARIZONA   SAN LUIS   SONORA
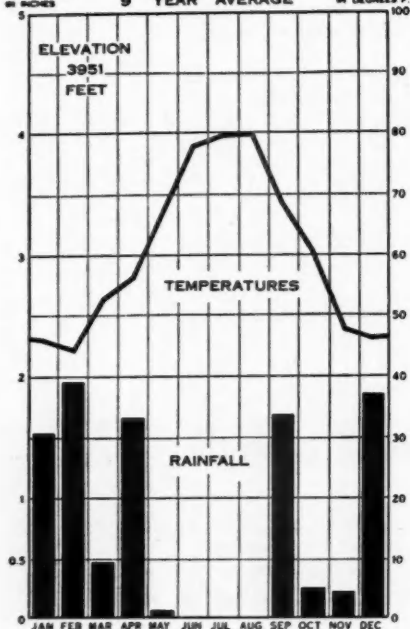
GUAYMAS   SONORA   NAVAJOA   SONORA

MAZATLAN   SINALOA   ISLA MARIA MADRE   NAYARIT
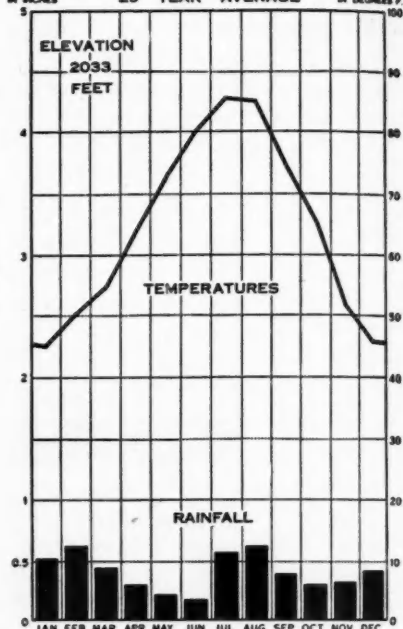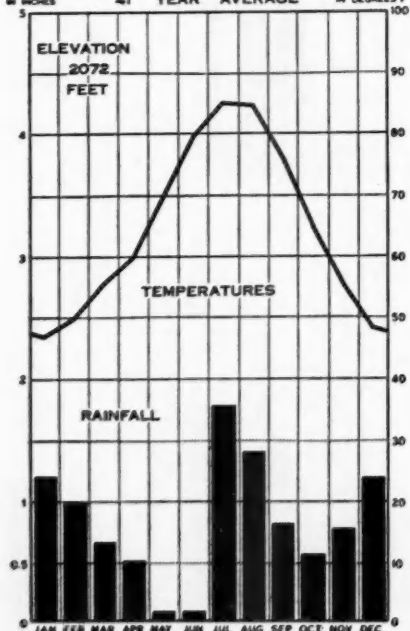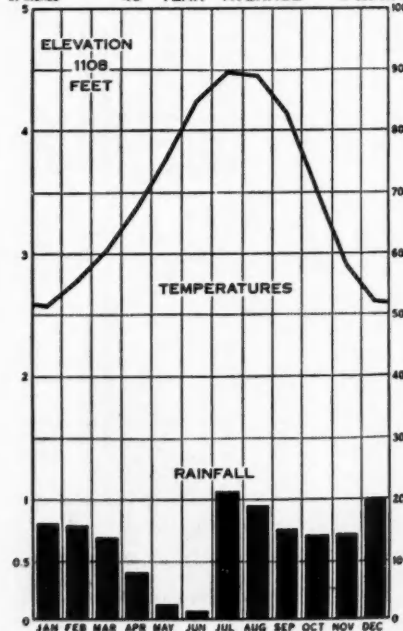
FIG. 12. Station charts for selected locations on the northeastern periphery of the Sonoran Desert. Note complex mixtures of rainfall regimes, further modified by altitude.

ST. GEORGE   UTAH
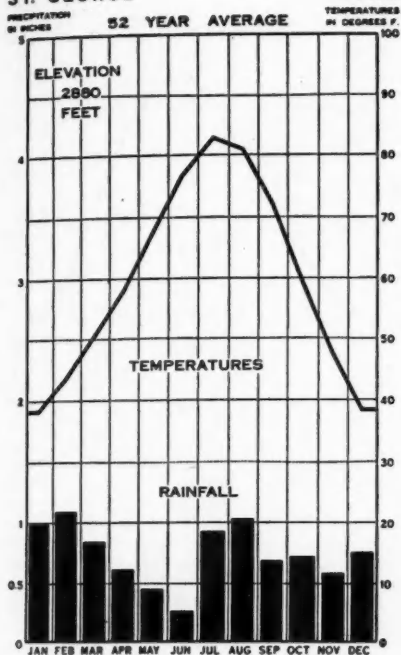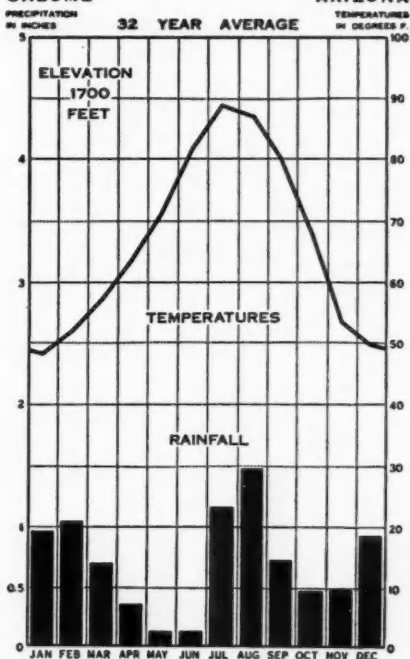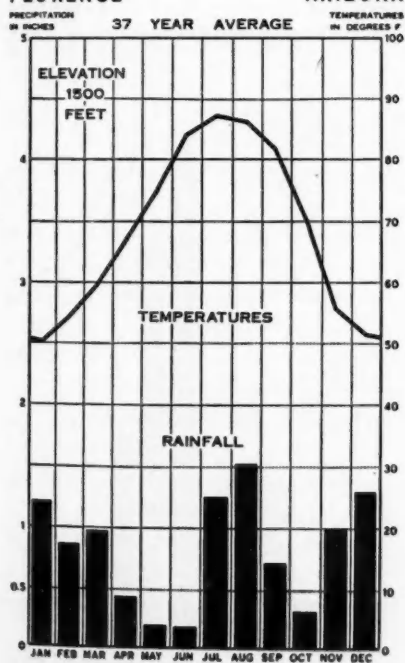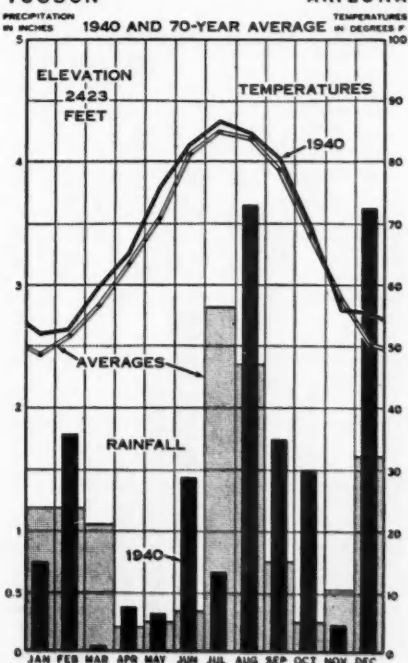
PRECIPITATION IN INCHES   52 YEAR AVERAGE   TEMPERATURES IN DEGREES F.

ELEVATION 2880 FEET

TEMPERATURES

RAINFALL

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

SALOME   ARIZONA

PRECIPITATION IN INCHES   32 YEAR AVERAGE   TEMPERATURES IN DEGREES F.

ELEVATION 1700 FEET

TEMPERATURES

RAINFALL

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

FLORENCE   ARIZONA

PRECIPITATION IN INCHES   37 YEAR AVERAGE   TEMPERATURES IN DEGREES F.

ELEVATION 1500 FEET

TEMPERATURES

RAINFALL

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

TUCSON   ARIZONA

PRECIPITATION IN INCHES   1940 AND 70-YEAR AVERAGE   TEMPERATURES IN DEGREES F.

ELEVATION 2423 FEET

TEMPERATURES

1940

AVERAGES

RAINFALL

1940

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
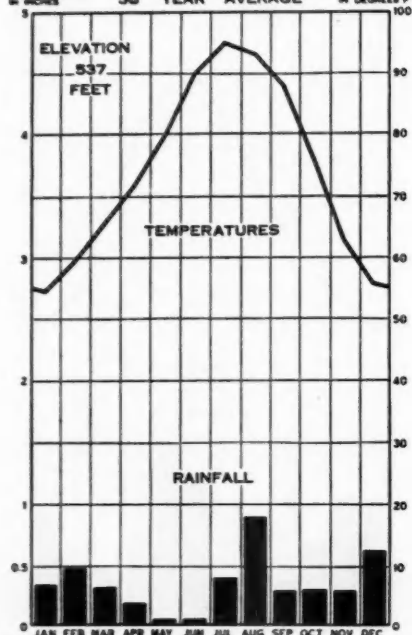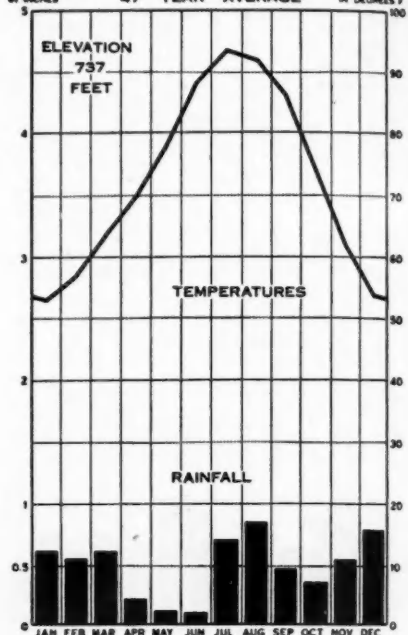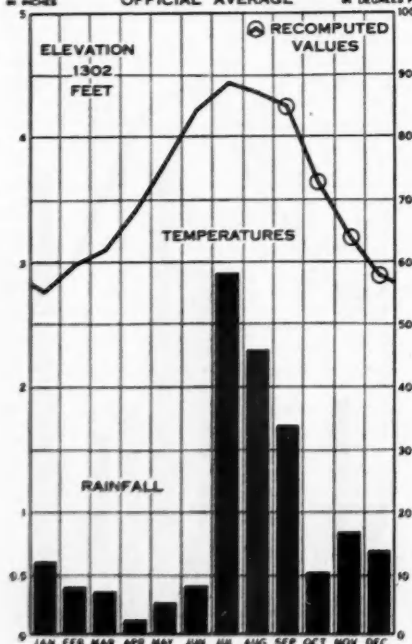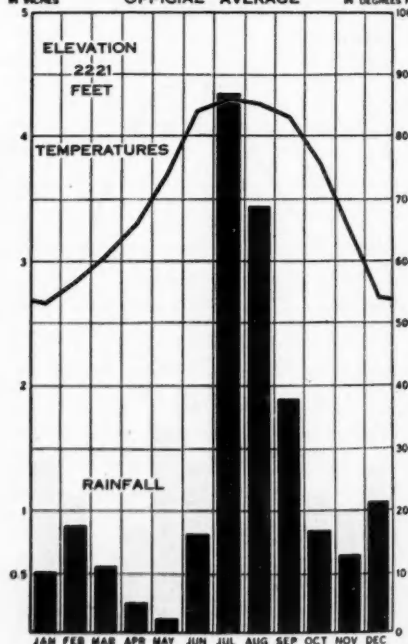
Fig. 13. Station charts for selected locations on the southeastern periphery of the Sonoran Desert.

AJO   **ARIZONA**

PRECIPITATION IN INCHES   26 YEAR AVERAGE   TEMPERATURES IN DEGREES F

ELEVATION 1763 FEET

TEMPERATURES

RAINFALL

NOGALES   **SONORA**

PRECIPITATION IN INCHES   OFFICIAL AVERAGE   TEMPERATURES IN DEGREES F

ELEVATION 3670 FEET

TEMPERATURES

RAINFALL

HERMOSILLO   **SONORA**

PRECIPITATION IN INCHES   20 YEAR AVERAGE   TEMPERATURES IN DEGREES F

ELEVATION 692 FEET

TEMPERATURES

RAINFALL

URES   **SONORA**

PRECIPITATION IN INCHES   OFFICIAL AVERAGE   TEMPERATURES IN DEGREES F

ELEVATION 1417 FEET

TEMPERATURES

RAINFALL

DERIVED RAINFALL FIGURES FOR PHOENIX, ARIZONA
PERIOD 1925-1945
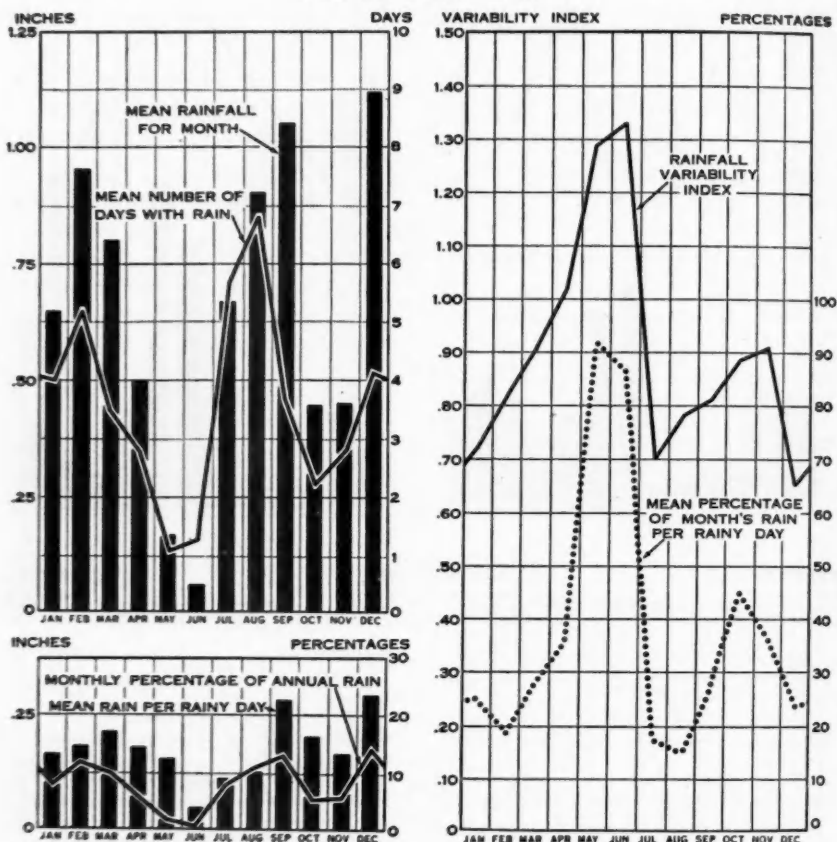
FIG. 14.   Derived rainfall figures for Phoenix, Arizona, for the period 1935–1945, inclusive.

are several areas, of relatively small dimensions, which have desert climates.   Several of these areas, notably those in the valley of the Little Colorado (Fig. 4, east of Gallup, N. M.), may be connected to the main desert by narrow "leaders", following the bottoms of the river valleys, in which there are no weather stations.

Charts for peripheral stations, near, but not within, the desert area, demonstrate the same mixed rainfall patterns as the desert areas.

SEASONAL RAINFALL CHARACTERISTICS

Because of the mixed rainfall regime in the Sonoran Desert, the problem of rainfall variations, and of rainfall forecasting, is not simple.   Further complicating

the problem is the location of weather stations near settlements, which, almost without exception, occupy sites more favorable to agriculture, and to other human activities, than the desert as a whole.   In consequence, all climatic descriptions prepared from available station records are inherently non-representative.

For the Sonoran Desert as a whole, there is a definite period of winter rains; and another definite period of summer rains, usually occurring late in the summer. A severe drought is the rule in the late spring; and a more moderate drought occurs in the fall.   A rainy day during the winter season is commonly characterized by a steady moderate rain, whereas a rainy day in the summer rainy season may receive all of its precipitation in an hour or so, with resultant flash and sheet flood; damage to crops, roads, and railroads; and accelerated gully erosion.

Derived rainfall figures for Phoenix, Arizona, a fairly typical desert station, so far as precipitation is concerned, for the period 1925–1945, inclusive, comprise Figure 14.   Mean rainfall by months, in this figure, computed from 21 years of records, is not in perfect agreement with the corresponding chart (Fig. 12), based on a 45-year mean.   This lack of agreement indicates that the 21-year mean is not stable, due certainly to its relatively short duration, and probably also to a minor climatic fluctuation.   A similar apparent shifting of rainfall means has been noted in other parts of North America.[24, 25]

The rainfall record for Phoenix (Fig. 14) shows a very rough correlation between the number of rainy days in a month and the rainfall total for that month. A close correlation is apparent between the mean rain per rainy day and the monthly percentage of annual rainfall total: the months that have the most rain also have the most rain per storm.

Rainfall variability at this station, as well as at most others in the Sonoran Desert, tends to be great when the amount of rain is small, and small when the total rainfall per month is great.   Also, rainfall variability tends to be high when the percentage of the month's rain per rainy day is also high.   As should be apparent from the curves (Fig. 14), the above statements are rough general rules, *not* invariant natural laws. Similar conditions prevail at other stations, notably Yuma (Fig. 5) in the desert, and in many locations far from it, such as Salt Lake City, Utah, and Bloomington, Indiana.

TEMPERATURE VARIATIONS

In contrast to the rainfall figures, temperature data from stations in and near the Sonoran Desert are consistent, and vary little from year to year.   The annual

[24] Because conventional statistical methods become somewhat vague when applied to excessively skewed distributions, such as the rainfall of the Sonoran Desert, conclusions obtained by computing the standard deviation, and then applying the principles of probability, as outlined by Pearson (see any modern statistics text), are questionable. As a rough working rule, a mean is considered stable to within one percent when the length of record equals 100 years multiplied by the index of variability (mean deviation divided by mean).

[25] Ives, R. L., "Recent Climatic Fluctuations in the Great Basin Region of the United States," *Weather*, III, 1948, pp. 374–379; "Rainfall Variability," *Proc. Indiana Acad. Sci.*, LVIII, 1949, 196–205.
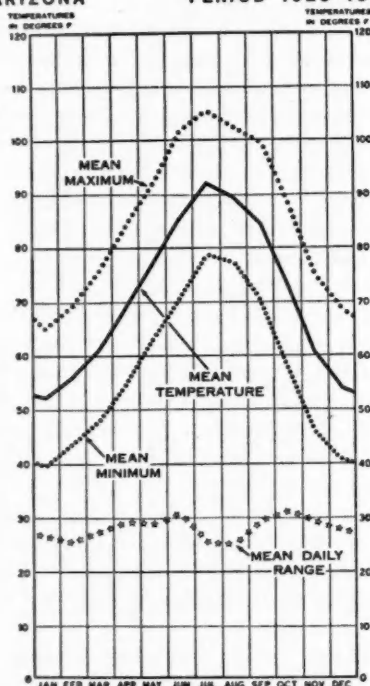
FIG. 15. Sample observed and derived temperature data for Phoenix, Arizona, for the period 1925–1945.

temperature cycle in the Sonoran Desert is relatively simple, and quite predictable.

The summer season in the Sonoran Desert is quite hot, with many days having a maximum temperature exceeding 100° F. Because of low relative humidities, sensible temperatures are tolerable, and complaints of summer season discomfort are heard largely from the obese, alcoholic, and neurotic components of the population. Provided water supply is adequate, and physiological salt-balance is maintained, hard outdoor work can be performed throughout the summer season, in this area, without physical damage.

The winter season, lasting three to four months, is cool, but not cold, and resembles the pleasant spring and fall days of the northern United States. Frost is uncommon in most localities; freezing temperatures are seldom reported; snow is almost unknown. Complaints of winter discomfort in this area are heard chiefly from the undernourished, aged, and neurotic.

Spring and fall, in this area, have moderate temperatures, and marked diurnal temperature variations, with little rainfall. This part of the year is commonly re-

garded as physiologically stimulating, although some efficiency experts classify these conditions as ideal for "blissful non-accomplishment".

Typical curves, showing observed and derived temperature data, for Phoenix, Arizona, for the period 1925–1945, inclusive, comprise Figure 15. Notable here is the constancy of the mean daily temperature range (mean value 27.8° F. for the year). Mean monthly temperatures, although variable, are remarkably consistent in their range (mean monthly variability 2.° F).

The foregoing curves appear to be a fair sample of conditions in those parts of the Sonoran Desert where records permit definite statements. Although they almost certainly prevail over all of the region, long-term observational data, necessary for rigorous verification of this extrapolation, still remain to be collected.

It should be emphasized that these temperatures are measured by standard weather-bureau equipment, in shelters with the instruments about five feet above the ground. Temperatures and temperature ranges measured closer to the ground surface will have much higher values and greater ranges. Diurnal ranges, at the ground surface, in this area, have exceeded 100° F. during a 24-hour period in several instances, and such ranges may be standard in barren deserts in the summer season.

LOCAL EVAPORATION FACTORS

Rainfall, in the Sonoran Desert region, is very scanty, and deficient at all seasons, as has already been demonstrated. Not only is the rainfall scanty, but it is ineffective, much of it being only token precipitation, which is evaporated almost as soon as it falls, bringing little agricultural water to the region. Although this finding is not rigorously demonstrated by instrumental observations over a long period of time, as is the regional high temperature and slight rainfall, it is very clearly shown by the nature and distribution of the regional vegetation, which is so admirably suited for an arid environment that it sickens and dies if the water supply is increased ("cannot stand prosperity").

So great is the evaporation rate in the summer season that a very small part of the summer rainfall is biologically useful, as is amply demonstrated by the sample records from Phoenix, Arizona (Fig. 16). Here, during the year 1945, which is chosen as a sample, factors favoring rapid evaporation reach their maxima during late spring and early summer, and remain high throughout the summer rainy season. In contrast, conditions are least favorable for rapid evaporation during the winter rainy season, so that the effectiveness of winter rainfall is many times that of summer rain.

Similar records are available for other years, and for a few other locations in the Sonoran Desert, and from them, similar, but by no means identical, conclusions may be drawn. Because of local factors, largely terrain, wind speed and percent possible sunshine vary considerably from place to place. An evaporation map for the entire region is intentionally omitted from this report because of absence of sufficient instrumental data to support the qualitative aridity conclusions drawn from regional vegetation and drainage pattern.

SUNSHINE, WIND, EVAPORATION AND
RELATIVE HUMIDITY FOR THE YEAR
1945 AT PHOENIX, ARIZONA.
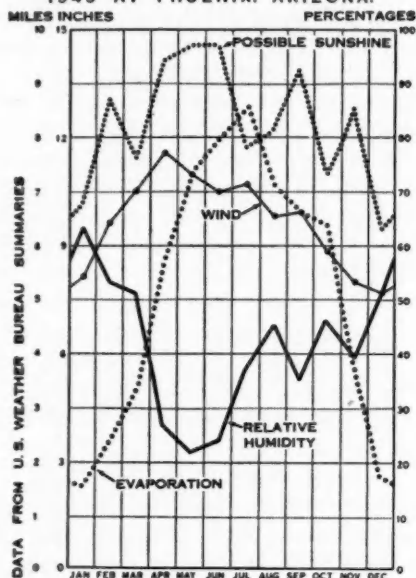
FIG. 16. Local evaporation factors at Phoenix, Arizona, for the year 1945. Possible sunshine and relative humidity are measured in percentages, wind in miles per hour, and evaporation in inches.

At present the best approximation of areal rainfall effectiveness is given by Thornthwaite's formulae (See footnote 16); which have been applied, in some detail, to Mexico by Contreras Arias (Footnote 6). As with other climatic factors in this area, evaporation determinations are not as complete as might be desired because of the wide separation of climatic stations, and the short duration of records at many of them, so that an unhappily large percentage of the averages are obviously unstable.

REGIONAL WINDS AND PRESSURES

Winds and pressures in the Sonoran Desert region are dominated by interrelations of the north Pacific High and Sonoran Low. Generalized arrangement of these controlling components is shown in Figure 17. The Pacific High moves northward in summer, so that its center is at about lat. 40° N.; and migrates south in winter, to about lat. 24° N., shrinking and weakening during its southward migration, growing and strengthening as it moves northward. The Sonoran low likewise has seasonal changes of central position and strength, but these appear quite complex. During the winter, the Sonoran Low is concentrated south and east
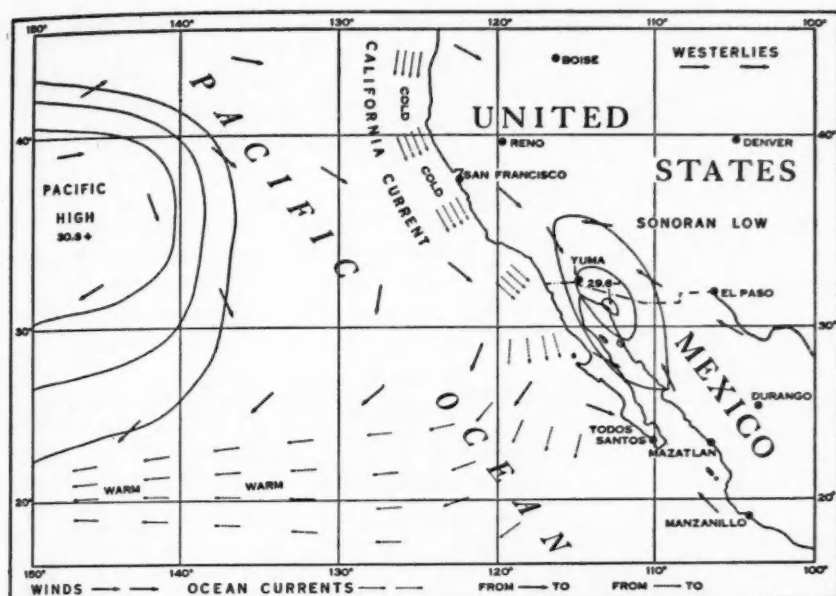
FIG. 17. Generalized pressure, wind, and ocean current map of the southwestern United States, northwestern Mexico, and adjacent seas.

of the mouth of the Colorado River, and is relatively weak.   Much field evidence suggests that the center of this low is over the Pinacate Peaks, of Sonora, Mexico (the Sierra de Santa Clara of the Kino reports and some modern European maps), a group of volcanic highlands, rising about 3500 feet above a plain of black lava about 30 by 50 miles in extent.   High surface temperatures and strong convectional updrafts are the rule in this area (Fig. 18) at all seasons.[26]   During the winter, the area north of the Sonoran Low is occupied by high pressures (the "Great Basin High").   In summer, the Sonoran Low expands, occasionally occupying the entire area from San Blas north to Pocatello and from the crest of the California Sierras east to the crest of the Wasatch.

During spring and fall, the Sonoran Low apparently breaks up into a number of discrete low pressure areas, of no great strength, which are centered over the major desert basins of the region.   In rare instances, the Sonoran Low, at its maximum extension, during the summer season, merges with another large low

[26] Thermocouple measurements on such lava surfaces show temperatures 20° to 50° (F.) above those measured five feet above the lava.   These high temperatures at the ground surface account for the previously somewhat mysterious disintegration of boots and feet in this area, as well as for the lack of foot infections in the lava beds.

Prevalent low pressures may account for the discrepantly high altitudes (up to 9,000 feet) given the Pinacate Peaks by some field workers.   Actual altitudes there are about 4500 feet above mean sea level, as determined by vertical angulation.

FIG. 18. Summary physiographic map of northwestern Sonora, Mexico, showing major terrain relations.

pressure area to the east. This is normally centered over the Bolson de Mapimi, in Chihuahua, Mexico, (Fig. 4); but occasionally expands so that it fills much of the Rio Grande Valley of New Mexico, and extends westward, along the U. S.—Mexican Border, toward Tucson, Arizona. Extent of the combined area of low pressure, at times, is slightly greater than that of the BWh area, as outlined by Trewartha (Fig. 4). When the low pressure area reaches its maximum extent, air circulation about and within it is somewhat erratic. When the extent is nearer average for the season concerned, winds at intermediate levels follow theoretical courses quite closely, so far as can be determined from available data, which are not complete.

Surface winds in the Sonoran Desert are not those indicated by simple theories, in most places, but consist of the resultant of the gradient winds and the local air-drainages. In consequence, winds at any specific location can be determined only by local observations. At distances a few thousand feet above the aerodynamic surface, however, a typical wind pattern (Fig. 17) prevails.

LESSER PHENOMENA

In addition to the larger climatic features of this area, several lesser phenomena are of climatic, geographic, or cultural importance. These, although small in actual magnitude, have rather great importance in their influence of some phase of human activity, and hence should not be disregarded.

VISIBILITY

It is commonly stated, in the Sonoran Desert, that visibility is limited only by the curvature of the earth. Visibilities of more than 50 miles are not uncommon. Unfortunately, however, clear visibility is rather sharply limited here, by both dust and optical haze ("shimmer"), leading to strict limitations on engineering, astronomical, and topographic work.

Due to very strong convections at all seasons, the air near the ground surface is in rapid upward motion, usually not uniform, during all daylight hours. In consequence, "shimmer" or optical haze, prevails during the daylight hours.

Because of mild and nearly continuous winds, suspended dust in the atmosphere produces a degradation in the visual contrast of distant objects, so that mountains on the horizon are seen dimly, if at all.

Rather thorough investigation of photographic visibility in this region discloses that a part of the obscuration of distant objects is caused by dust. Were obscuration and decay of definition due entirely to fine dust, use of infra-red sensitive photographic materials should bring about a marked improvement in quality. Use of infra-red photography does improve definition and contrast somewhat, but does not eliminate the desert haze, indicating that a large part of it is due to air instability, or optical haze, a conclusion supported by ground observations.

Mirages

Common to the Sonoran Desert are "water," or inferior mirages, produced by refractive effects in the heated layer of air quite close to the ground. These mirages are common, standard, and may be explained and predicted by methods shown to be valid in many other parts of the world.

Less common in this area are superior and multiple mirages, occurring when the lower layers of air are thermally stratified. These are particularly common over the Gulf of California, and on the west side of Baja California, where the California Current (Fig. 17) chills the lowest stratum of air, producing great stability, and leading to stratification.

Near the sea, particularly in areas where high mountains are quite close to

shore. Fata Morgana mirages are not unknown, and lead to annoying or serious misobservations by navigators and pilots. Conditions producing the Fata Morgana have been described elsewhere.[27] In general, mirage conditions in the Sonoran Desert, although apparently extreme to observers from nondesert environments, are entirely normal to the region, and may be accounted for, in their entirety, by principles already well known and understood.

Minor Vortical Disturbances

The extreme thermal instability, developed near the surface in the Sonoran Desert on most sunshiny days, is commonly relieved by small, but intense, vortical disturbances, which are locally known as dust whirls, dust devils, and diablos. These, of small areal and vertical extent, carry large volumes of dust upward as they relieve cumulated local instabilities, giving them great visibility.

Commonly, dust devils are not dangerous, do no material damage, and pass rapidly over large areas of desert, leaving no lasting evidence of their passage. In the vicinity of the Gulf of California, however, vortical disturbances, resembling dust devils on land, and waterspouts when over water, reach rather great heights and become violent enough to capsize small craft. These disturbances, which are sometimes called *chubascos,* have some of the characteristics of a tornado, and deserve further study.

Extreme development of dust devils have been noted by the writer in the Ajo Valley of Arizona, where they appear to have a somewhat systematic behavior on windless days.[28] A fairly detailed study of the relations between theoretical aerodynamics, and the behavior of dust whirls at Inyokern, California, has recently been published by Williams,[29] and merits inclusion in the "required reading" list.

Fogs

Extensive fogs in the Sonoran Desert and its environs are of two entirely different types, both of which are rather predictable.

Common on the west coast of Baja California, and uncommon in other parts of the desert, is the typical "California Fog," also noted at such locations as Santa Monica, California, and San Diego. This fog, which is limited to the coastal area by the peninsular "backbone," is caused by the interaction of the California Current (cool) with local air drainages (cold) and with incoming air from the Pacific High (Fig. 17) (warm aloft, cool below, very stable).

The second fog type is common along the shores of the Gulf of California, and to a lesser extent in the southern part of Baja California, near Todos Santos. This occurs when the area is invaded by cold air, usually of Great Basin origin ("north-

[27] Ives, R. L., "Meteorological Conditions Accompanying Mirages in the Salt Lake Desert," *Journ. Franklin Inst.* CCXLV, 1948, 457–475; and included bibliography.

[28] Ives, R. L., "Behavior of Dust Devils," *Bull. Amer. Met. Soc.,* XXVIII, 1947, pp. 168–175.

[29] Williams, N. R., "Development of Dust Whirls and Similar Small-scale Vortices," *Bull. Amer. Met. Soc.,* XXVIII, 1948, pp. 106–117.

ers", "norte"), and the waters are relatively warm.   This condition, most common in winter, produces light to dense fog, causing acute discomfort to local residents, who are acclimated to high temperatures, and to medium or low humidities, and who habitually dress for a hot climate.   Because these winter fogs cause so much discomfort, and may last for several days at a time, residents of the areas near the Gulf of California remember them to the exclusion of the heavier rains at other seasons (which cause little discomfort), and report, in good faith, that the local rainy season is winter.   These winter fogs, which seldom produce more than 0.01 in. of precipitation plus condensation, are commonly referred to as "lloranas".

CONVECTION AND SUBSIDENCE

Vertical air motions in most parts of the Sonoran Desert are quite complex, with convection extending (theoretically) nearly to the stratosphere; and subsidence of air from the stratosphere or substratosphere taking place regularly.   Various lateral migrations at several levels are also indicated by observations, which are not yet extensive enough to give a rigorous quantitative analysis of all air motions.

Complicating the convectional picture is the effect of terrain, which produces a definite localization of strong convectional updrafts (during the day) over topographic highs.

Here convectional updrafts, made obvious by crest clouds, bear a definite relation to the trends of the mountains, even though the mountains are not very high, and the relative humidity of the air is initially rather low.

This strong convectional cycle is also evidenced by a marked diurnal cycle of barometric variations (previously mentioned), and by the presence, on most clear days, in most flat areas, of mirages and dust devils.

In the large "blind" basins of this area, many of them occupied by salt pans in the lowest parts, a diurnal wind cycle is also apparent, and is related to the daily convectional cycle.   Shortly after sunrise, winds blow outward from the center of the basin, and increase in intensity and temperature during the day.   Shortly after sunset, the winds reverse, currents now flowing from the valley periphery toward the center.   These winds, during the early part of the night, are hot and very dry, and are probably composed largely of adiabatically-heated subsided air from far aloft. In most areas, on most clear nights, the temperature of the wind declines toward morning, and may be quite low by dawn.   In a few areas, notably Death Valley, California, the hot wind may continue until dawn.   This is the famous, and deservedly feared, "furnace wind."

Smoke tests in a few desert basins occupied by salt pans show that vertical convections continue in the center of the basin (over the salt pan) for several hours after the peripheral indrafts begin, and also indicate that, except where there is a salt pan or lava floor, upward air motion stops soon after the area is in shadow.

General mechanics of playa convections is about the same wherever encountered, but details and timing differ from playa to playa.   In consequence, air motion on and near the divides between desert basins, particularly those of different sizes, and with differing floor soils, can be determined only by direct observation.

ORDINARY AIR-MASS PHENOMENA

The Sonoran Desert Region, as a whole is dominated by Tropical Maritime air, more or less modified, at all seasons. This air flows in to the region from both the Gulf of Mexico and the Pacific, the inflow being greatest during the summer season.

Tropical Gulf air, to enter the region, must follow a long overland trajectory, crossing the Continental Divide in its course. In natural consequence, this air is somewhat modified in transit. That part of the Tropical Gulf air which crosses the Bolson de Mapimi is most greatly modified, as it loses some moisture in crossing the Sierra Madre Oriental of Mexico, then is diluted by convective return air over the Bolson de Mapimi, and then crosses the arid ridges of the Sierra Madre Occidental before reaching the Sonoran Desert. Air which enters via the Rio Grande Valley is diluted with convective return air, lowering the relative humidity. Air entering by either course increases in temperature in transit, during the summer season, so that its relative humidity tends to be low.

Tropical Pacific air, to enter the region, must pass over a large area of desert or shallow sea (the Gulf of California), and hence arrives in the Sonoran Desert convectively diluted and warmer (during the summer) than at its point of origin, and also with low relative humidity.

Tropical Maritime air, of whatever origin, is diluted in transit not only by purely convective air, but also by subsided Superior air, which has a low specific humidity aloft, and warms by compression in descent. This dilution also reduces the relative humidity of the Maritime Tropical air, so that it acquires many of the characteristics of Continental Tropical air, and is so designated, on arrival in southern Arizona and adjacent regions, by many meteorologists.

Invading this region quite regularly (about once in three days) are tongues of northern air, usually Polar Continental or greatly modified Polar Maritime, which in other regions are productive of heavy rainfall. Here, because local air is dry, and the invading air is also not only dry, but quite warm, relative to its source, passage of a front is only rarely accompanied by precipitation. In fact, many of the fronts are so weak that they are detected with difficulty.

In consequence of the modification of most incoming air, frontal disturbances are extremely uncommon in the summer season, but bring much of the rain in winter, when the modifying influences are least, the mean position of the polar front is farthest south, and air-mass temperature contrasts are greatest. Because no air can enter the Sonoran Desert from Polar source areas by any ordinary path without crossing highlands having a minimum altitude of about 6,000 feet, the effects of air-mass invasions from the north are relatively small, in this area, at all seasons. Only the most violent disturbances, in general, "get through" to the Sonoran Desert without great modification.

OTHER EXTRANEOUS FEATURES

Although migratory cyclones and air-mass invasions of the Sonoran Desert are not commonly bringers of "weather," two very strong types—the tropical cyclone

and the "norther"—are noted in the region, and cause violent, although short-lived, changes in precipitation and temperature.

Tropical cyclones, which are also known as hurricanes, or, in this area as "Cordonazos de San Francisco," are most frequent in late summer.   Although as many as 14 may occur in an average year in Mexican west-coast waters, less than half of these impinge upon the land, and only two or three, in an average year, reach the Sonoran Desert.

Sample hurricane trajectories, for the calendar year 1936, as plotted by the U. S. Weather Bureau and the Servicio Meteorologico Mexicano, are shown in Figure 19.   Here, of the four hurricanes plotted for west-coast waters, only two
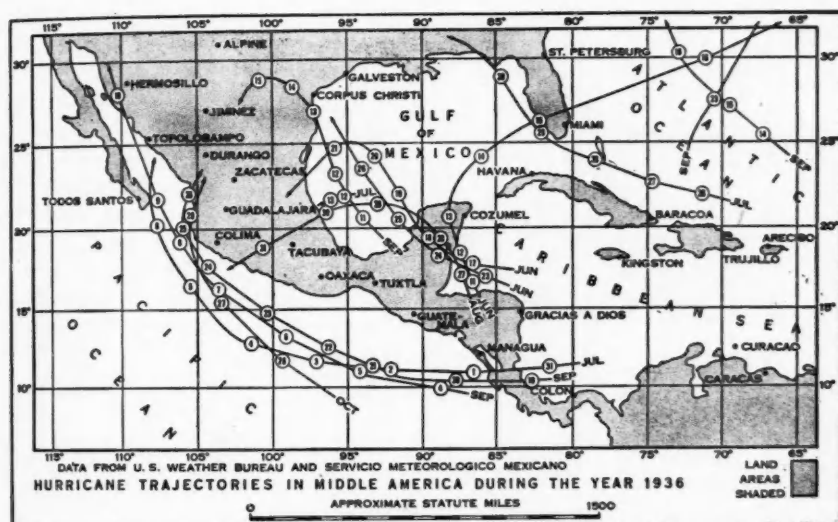
FIG. 19.   Hurricane trajectories in middle America during the calendar year 1936.

entered the Sonoran Desert, and one of these was, in all probability, a "glancing contact".

Few of the hurricanes or tropical cyclones which enter the mainland portions of the Sonoran Desert cross it, because only an exceptionally strong hurricane, under very favorable conditions of humidity and temperature, can continue in existence over a land area.   Those few hurricanes which move inland, however, produce, in a few hours or days, in a restricted area, rainfall equal to or exceeding the annual average for the area.   One very clear example of this, the hurricane of Sept. 30, 1921,[30] brought 3.63 inches of rain to Yuma, Arizona, where the mean annual rainfall is about 3.47 inches.

[30] Hurd, W. E.   *Tropical Cyclones of the Eastern North Pacific Ocean*, U. S. Hydrographic Office, Washington, Edition 4, 1944.

FIG. 20. Genesis and dissipation of a "cold dome", showing the life history of an exceptional norther, as well as related phenomena.

Although observational data from this area are still not as complete as might be desired, it appears that an appreciable part of the rainfall variability of the Sonoran Desert (Fig. 5) is due to hurricanes, and to tropical cyclones of less than hurricane intensity.[31]   Extension of the weather-reporting networks of both the United States and Mexico, now under way as funds permit, may soon clarify the relation of tropical cyclones to rainfall variability in the Sonoran Desert.

Northers, known in Spanish-speaking areas as *nortes,* are not as common nor as intense in the Sonoran Desert as they are in the areas east of the Continental Divide, but they are important causes of agricultural and range losses, and a few of them cause very intense discomfort in those parts of the region where frost is nearly unknown.

Northers are outbreaks of very cold air, usually from the northern Great Basin, which commonly occur when a very strong high pressure area "camps" over the Snake River headwaters. In many instances, the same high pressure that produces a norther in the Sonoran Desert also produces dense fogs in the Great Valley of California, and chinooks in the foot-hills area in Colorado and Wyoming.

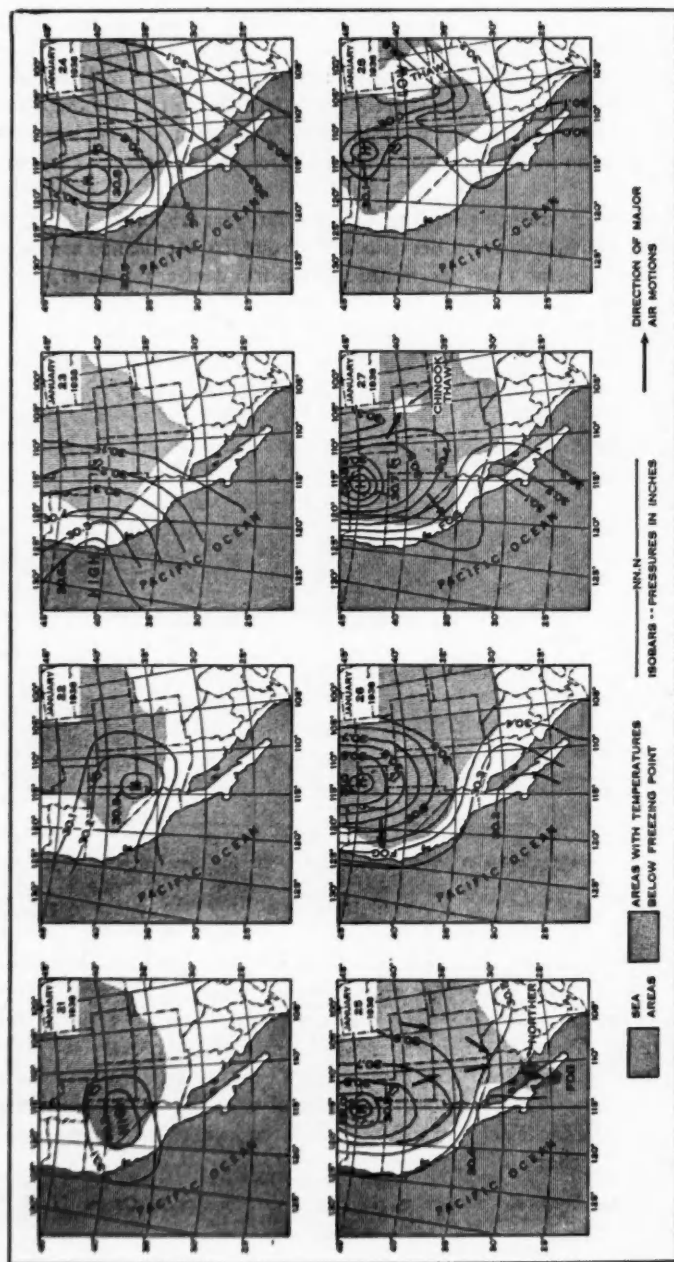Genesis and dissipation of an exceptional "cold dome" over the Idaho lava beds, with its characteristic accompaniment of California fogs, northers, and chinooks, is shown in Figure 20; an abridged version of a sequence of maps prepared by the U. S. Weather Bureau, with some data, secured from local observations, added.

This particular norther, which brought frost and freezing temperatures to areas which had been frost-free for almost two generations, caused an enormous amount of human discomfort, and may have damaged the endemic desert flora severely.[32] A norther is usually accompanied by light to dense fogs over the Gulf of California, and more rarely over the Salton Sea; and usually is preceded by a strong, dry, and rapidly-moving front, not always shown on synoptic maps.

In some instances and areas, the cold air comprising the norther is relatively thin, and is separated from the superjacent air by a strong inversion. In parts of the lower Colorado Valley, some northers behave as density currents, and resemble, on a large scale, the katabatic winds characteristic of most mountain valleys.

In a majority of instances, the air circulation comprising a norther in the Sonoran area is from the source high to the approximate center of the Sonoran Low (Fig. 18). Only when the source high is particularly persistent, and the amount of air in transit is great, does the norther proceed far south of about Lat. 30° N. When this does take place (as in Fig. 20), the Sonoran Low is temporarily obliterated, and air motion is from the source high (usually in the Snake River lava

[31] Ives, R. L., "Mexican West-Coast Hurricanes," *Proc. Seventh Pacific Sci. Cong.* in press.

[32] The amount of plant damage caused by this norther is still a matter of conjecture. That the plant damage occurred and was evident in the summer of 1938 is undeniable, but a part of the damage seems due to disease, rather than to direct chill. It is entirely possible that local plants, such as the Saguaro cactus, are normally immune to local bacteria, but become susceptible after extreme chilling, in much the same manner that many healthy humans contract pneumonia after inhaling phosgene. Evaluation of the primary and secondary damage to vegetation as a result of northers and other climatic adversities is quite important agriculturally, but is in the realm of plant pathology, rather than of geography.

plateau) to a low in the general vicinity of the Oceana Bank (Lat. 9° N; Long. 116° W.).

Forecasting of both tropical cyclones and northers in the Sonoran Desert area is at present rather unsatisfactory, despite rather marked improvements within the last decade, because of the small number of reporting stations.

THE SONORAN MONSOON

Inspection of the pressure and wind patterns of the Sonoran Desert and adjacent land and sea areas disclose a seasonal shift in the position of the Pacific High; a reversal of the pressure in the northern Great Basin from low in summer to high in winter; and a season variation in the size and intensity of the Sonoran low, which is largest and strongest during the hot season. These factors are qualitatively similar to those producing the Indian Monsoon, yet the Sonoran Desert is a region of marked aridity, whereas some places in the path of the Indian Monsoon, such as Cherrapunji, in the Khasi Hills (more than 400 inches of rain annually) are among the wettest places on earth.

During the summer season, the Sonoran monsoon produces some heavy rains in the higher parts of the Sonoran Desert and of the Arizona plateau region on its northern boundary, but these rains are heavy only by comparison with precipitation on the flatlands, and seldom exceed 60 inches, even in very small areas, such as the forest between McNary and Showlow (Ariz. Fig. 2). Moderate to light rains occur over most of the desert area, and are due to convective uplift of the moist monsoon air. As the relative humidity of this air, on the desert floor, is low, uplift to 8,000 feet, or more, is usually necessary to produce precipitation.

Generalized air circulation patterns during the summer show that the Sonoran Monsoon has a lateral infeed, receiving air from high pressure areas at about Lat. 38° N. Air entering the Sonoran Desert from the Atlantic High is stripped of a large part of its moisture in transit across the Chihuahua—Texan highlands, and is diluted with subsided superior air during its travels. In consequence, Tropical Atlantic air, as modified in transit, brings little available moisture to the Sonoran Desert.

Air from the Pacific High is initially dry, because of descent, and picks up little moisture in transit across the northeast Pacific, because of great stability and cool currents across its trajectory (Fig. 17). A part of this moisture is stripped out, before the air reaches the desert area, by crossing the Sierras and the peninsular ranges, and convective dilution occurs here also.

Small inflows of very moist air are noted at times from the Tres Marias vicinity toward the Sonoran Desert. This air, at its source, is nearly saturated, but is warmed in transit, and diluted with convective return air, so that, on arrival near the Arizona—Sonora boundary, its relative humidity is low.

Thus, although there is a definite inflow of air to the Sonoran Desert during the summer season, this air is not very moist to begin with and it loses much of its relative humidity and a smaller part of its specific humidity, in transit. Otherwise

stated, the loading and transporting mechanism of the Sonoran Monsoon is not very effective.

Much of the notable precipitation from the Indian Monsoon is caused by the vertical deflection of the inflowing air currents as they cross the Himalayas (more than 15,000 feet high) to reach the low pressure area concentrated over the Tarim Basin. In very marked contrast, the concentrated low in the Sonoran Desert is to windward of the Mogollon Rim (aerodynamically less than 7,000 feet high) during the summer season, so that much of the maritime air is dissipated in this low, and only a small part rises over the highlands to produce orographic precipitation. In consequence, the Sonora monsoon is not only a poor bringer of moisture to the Sonoran Desert, but has an inefficient dumping mechanism, so that it cannot precipitate much of the small amount of moisture which it does bring into the area.

The winter phase of the Sonoran monsoon is even more disappointing, consisting only of intermittent weak outflows of cold air from the northern Great Basin to the central Sonoran Desert. Little moisture is transported; there being a minimum of moisture picked up in the source area; an increase in temperature toward the delivery area; and little cause for moisture loss in the terminal area, which is the very weak winter center of the Sonoran low.

EXCEPTIONAL AREAS

In the foregoing discussion, climate of the Sonoran Desert as a whole has been described, insofar as the evidence permits. The general average, however, is not the invariable condition, and many parts of the Sonoran Desert, due to relatively minor changes in topography or other factors, enjoy environmental conditions which are favorable to agriculture. Most of the large settlements, such as Phoenix, Tucson, and Yuma, owe their existence to water diverted from rivers which originate outside of the desert. Many of the smaller settlements were founded as stage stations at places where streams or wells made water available. A typical oasis in this region is the town of Sonoita, Sonora (Fig. 1), on the ephemeral river of the same name. Here, due to a happy combination of bedrock-alluvium relations, agriculture is not only possible but profitable, and permanent water supply is available due to a funneling of the drainage of a large area through the deep canyon of the Sonoita River just east of the town.

In prehistoric times, Sonoita was a semi-permanent or permanent agricultural settlement. After the introduction of livestock by Eusebio Kino in 1698, the local economy expanded. Since that time, by use of good sense and enormous amounts of hard work, the farming area has been expanded, the irrigation works improved, and numerous wells have been dug. The area now contains a prosperous and nearly self-sufficient farming community of about 800 persons.

Although the return from attempts at subsistence agriculture in typical desert areas is not equal to the seed planted, some desert areas, skilfully used, at exactly the right time, can be made to give a good return. The best example of this is the *temporale* agriculture of the Pima-Papago people, who, as a result of careful

observation and long experience, know exactly where runoff from the erratic summer rains will be concentrated and retained.   By planting in these specially favored locations at exactly the right season, as determined by several generations of experience, the Pima-Papago are able to raise excellent crops of corn and other foods about six years out of seven.   When no rain whatsoever falls in the region, the crop is lost, as might be expected, but by planting in many scattered areas, in different watersheds, there is very seldom a "starving year" despite the vagaries of desert rainfall.   As nearly as can be determined from present evidence, this *temporale* agriculture has been practiced successfully by the Pima-Papago and related groups for more than 2,000 years.

In the Sonoran Desert there are also exceptional areas of another type—areas where nothing will grow, even with irrigation.   These consist of the great salt beds along the shores of the Gulf of California, the Pinacate Lavas, and the saline floors of the larger playas.

SUMMARY OF CLIMATIC MECHANICS

From the foregoing descriptions, it should be apparent that the Sonoran Desert is a true desert by any rational criterion, and that the rainfall is very deficient at all seasons.

Causes of this regional aridity are, in summary:—

1. Desiccation of air incoming from the north, west, and east by passage over relatively high mountain barriers.

2. Desiccation of air, incoming and in place, by convective uplift, mixing with subsiding "Horse Latitude" air, and subsistence of the mixture.

3. Heating of air incoming from the south, so that its relative humidity is reduced greatly.

4. Southward location of the area relative to the mean position of the Polar Front.

5. Overall weakness of the "Sonoran Monsoon," and its inefficiency as a rainbringer.   This is due in large part to the unfavorable location of physiographic features with respect to the regional pressure and wind pattern.

APPENDIX A

PHASE RELATIONS

Many of the systems of climatic description now in use tend, by use of a "pigeonhole" classification, to mask the gradual transition from one climate to another, and to substitute for it, in the mind of the average student, a false concept of abrupt change.

Several other systems, notably those employing De Martonne's index of aridity, or a similar concept, successfully avoid the "pigeonhole" approach, but in so doing tend to conceal many other real and pertinent relations, such as the seasonal distribution of rainfall.

By appropriating several of the concepts of electrical engineering mathematics, via harmonic analysis and electrical analogue computation, it is possible to describe most of the standard climates simply and tersely in terms of the familiar index of aridity, and the phase relationship of temperature and rainfall.

The phase relation can be stated most simply as the temporal relation between temperature maximum and precipitation maximum. Two illustrative examples of phase relations are shown in Figure 21 (top). In this figure, at Sao Paulo, the precipitation maximum leads (comes before) the temperature maximum by about 30° or arc (one year being a complete cycle of 360°), or one month. At this station, as at most other locations in the savanna, precipitation and temperature are very nearly in phase with each other (and with insolation maximum above the cloud level).

In contrast, at Tiberias, Palestine, an arid Mediterranean station, the precipitation maximum lags (comes after) the temperature maximum by about four months. Here, as at most other Mediterranean stations, precipitation and temperature are distinctly out of phase (in some instances by about 180°).

At stations where the temperature and precipitation curves are fairly simple, the phase relations can be determined, for ordinary descriptive purposes, by inspection. A more rigorous presentation is possible when the rainfall curve is quasi-sinusoidal, and rainfall distribution, in such an instance, may be approximated by:—

$$P = A + B \sin \theta$$

In which:—

P = Precipitation at any given time (short interval, such as one week)

A = Mean rainfall for the year

B = Maximum rainfall for a given time interval (same as in A) during the year

θ = Time since rising precipitation curve crossed mean value, expressed as an angle (days elapsed divided by 365.244 and then multiplied by 360°: for most work, the relation days = degrees is adequate).

Similarly, temperature may be expressed by the formula:—

$$T = C + D \sin \theta$$

and the phase difference between temperature and precipitation, indicated by θ, is determined from the temporal difference between analogous parts of the curves, such as maxima.

Whereas temperature curves may almost always be approximated by trigono-
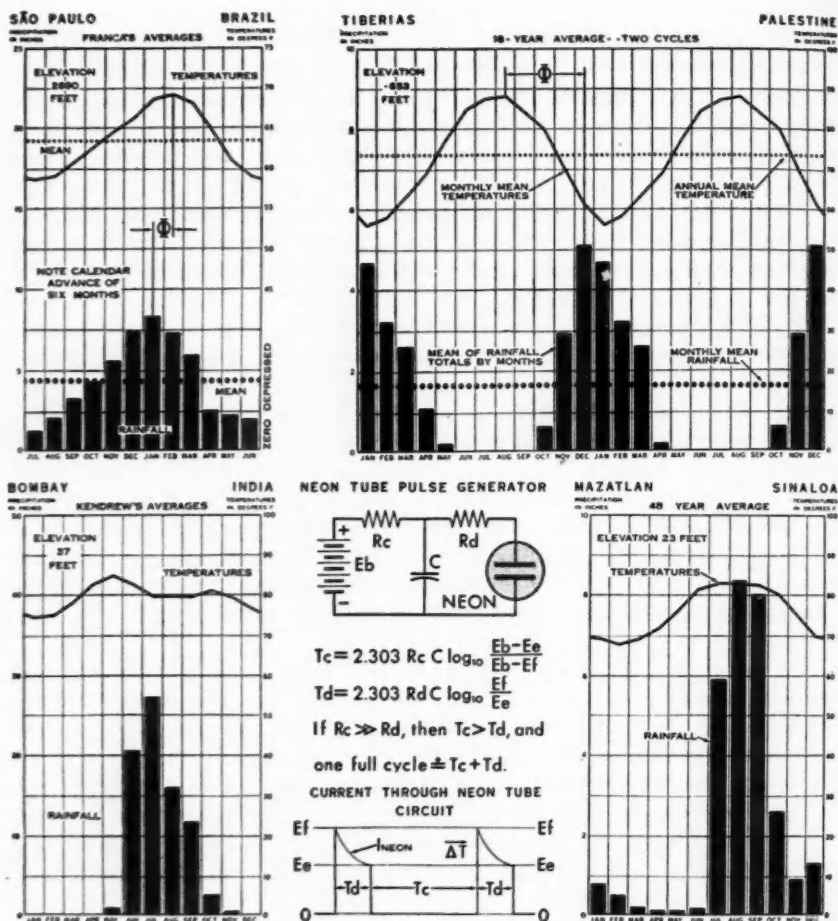
FIG. 21. Phase relations. Top: Temperature—precipitation relations for upland savanna and Mediterranean climate. Bottom: Examples of pulse and mixed rainfall regimes, with a simple pulse generator and its equations.

Symbols are:—

Tc = time (seconds) necessary to charge condenser C to Ef from Ee.
Td = time (seconds) necessary to discharge condenser C to Ee from Ef.
 C = capacity of condenser (farads).
Eb = battery voltage.
Ef = firing voltage of neon tube.
Ee = extinction voltage of neon tube.
Rc = resistance of charging circuit (ohms).
Rd = resistance of neon tube circuit (ohms).
Ineon = current in neon tube circuit (amperes).

metric formulae (not always as simple as the examples given), some rainfall curves are definitely not only nonsinusoidal, but appear to be logarithmic "attrition" curves, suggesting definite pulse or surge phenomena. Such a curve is shown on Figure 21 (Bombay), where the rainfall pulse is produced by the breaking of the monsoon. The curved onset shown here is largely due to the variations in the timing of the monsoon, each individual year having a much sharper onset of the rainfall maximum than is shown by Kendrew's mean value.

Such pulse variations are common physical phenomena, and may be duplicated to any accuracy desired (except 100 percent) by a simple neon tube oscillator, (Fig. 21, center), or simple modifications thereof. In this device, monsoon rainfall is approximated by current flow through the neon tube circuit. By inserting inductances at strategic points in the circuit, the various current and voltage curves can be modified to duplicate climatic curves of some complexity.

By careful inspection, followed by elementary harmonic analysis, the various types of rainfall in a mixed regime can be isolated and evaluated. One example of this, the record for Mazatlan, Sinaloa, at the northern edge of the western Tierra Caliente of Mexico, (Fig. 1; Fig. 21, right) is presented as an illustration. Here, by inspection, it can be seen that the rainfall is dominated by a surge, in the summer season. Also plainly visible is curve of a relatively weak rainfall regime almost 180° out of phase with the temperature curve. When the winter rainfall is approximated by a sine curve, whose value is subtracted from the totals, month by month; and the summer rainfall is likewise represented by a fitted pulse curve, which is likewise subtracted from the totals; the residual is a weak quasi—sinusoidal curve, roughly in phase with the temperature curve, representing the savanna-type rainfall. Some stations have much more complicated rainfall patterns than this example.

In very general terms, the following indications are given by temperature—rainfall phase relations:—

1. When temperature and rainfall curves are sinusoidal and nearly in phase, a dominance of convectional rainfall is indicated.

2. When the rainfall curve is a definite surge or pulse, taking place near, but not necessarily at, the temperature maximum, or between two temperature maxima separated by less than six months, a monsoon tendency is indicated.

3. When temperature and rainfall curves are sinusoidal and four or more months out of phase, a dominance of frontal rainfall types is indicated, with a strong possibility of cyclonic storms, which reach a maximum at the time of maximum rainfall.

These indications, it should be noted, are only approximate, and should be regarded only as rough working rules for which the practical limitations have not yet been determined. Further investigation and evaluation of this method of climatic analysis seems in order, as it, in conjunction with comployment of an index of aridity, or some similarly derived figure, offers some hope of producing a rigorous system of climatic description which does not suffer from the "pigeonhole" heresy inherent in the presently accepted systems.

SOME PRELIMINARY NOTES ON THE USE OF THE LIGHT AIRPLANE AND 35MM. CAMERA IN GEOGRAPHIC FIELD RESEARCH

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THE PROBLEM

THERE is considerable agreement among geographers that the inadequacy of available reconnaissance and inventory tools imposes a serious handicap on present-day geographical field research. This lack of tools results in excessively heavy demands both on the time and effort of the investigator, with the general result that geographic research is to a degree restricted. Consequently, there is an ever-pressing need for new kinds of field tools and techniques to supplement those already in use.

Since geographical field research centers largely on the study and inventory of areal distributions and pattern associations, it long has been the geographer's hope to be able to view the manifold features of the landscape in their complex totality from vantage positions overhead.

New tools and techniques which will furnish the field geographer with the great advantages of direct overhead observations and rapid and free movement are highly desirable. Equally desirable are new tools which will permit him personally to record his data photographically from overhead for future detailed study.

OLD TOOLS IN NEW ROLES

Pursuant to this need, the writer has experimented, over a period of four years, with the common light airplane and the ordinary 35mm. camera as an inexpensive and versatile field tool combination. Neither of these tools in themselves is new, it is only in a role as possible aids in further expediting field reconnaissance and detailed inventory work that they are new.

Preliminary experiments were made immediately following World War II. Much more complete and conclusive experiments were carried out in a full-scale study of the Santa Maria Valley in Southern California during the summer of 1947. Further experimentation continues in the Santa Barbara portion of the same general region, with promising results.

Uses in Field Reconnaissance: Regional Appreciation

The logical beginning of the study of any geographic region is a comprehensive field reconnaissance. Unfortunately, this initial investigation is all too often unduly abridged, or even omitted completely. Such sacrifices in regional acquaintanceship and appreciation frequently stem from the everwhelming pressure for time. By

ordinary ground procedures, even limited reconnaissance of an area may require days or even weeks, the time varying directly with such factors as difficulty of terrain, type of vegetation cover, season of the year, and surface transportation facilities.

Field reconnaissance and regional appreciation can be expedited tremendously by the use of the light airplane as an unfettered means of movement over and across an area. The geographer may thus free himself of surface obstacles and move speedily and methodically wherever the occasion demands—cutting at will across mountain ranges, deep gorges, deserts, swamps, or forests. Observations may be made leisurely from the plane at any desired altitude: from tree-top levels for detailed close-up study, or from mile-high heights for en masse regional pattern appreciation. Regional understanding and "feeling" can be acquired to a degree not obtainable in any other way. Flight speeds may be varied sufficiently to allow the investigator to make voluminous field notes while in flight, or to plot pattern lines directly on transparent overlays on base maps or photographic mosaics. Also, transitional zones can be more fully appreciated and given their just consideration. Regional boundaries can be seen and studied in reality, not simply as abstract lines and symbols on sketches and maps. And by means of overall direct visual study "core areas" define themselves more readily within the investigator's general regional consciousness.

On the basis of experiments conducted to date, it is believed that the ideal field reconnaissance will eventually evolve from a complementary use of both ground observation and aerial observation.

Uses in Field Inventory: Type-Study Aerial Photography

It is recognized that commercial aerial photography provides many vital links in the chain of inventory data so important to the solution of geographic field problems. However, the field geographer faces the fact that in the past he has not been master of the tools of production of such aerial photography. These are available today only through normal commercial channels. He can avail himself only of the recorded product of those tools—the printed picture which he has had no hand in composing or making.

But now, the geographer can provide himself with personalized aerial photos as supplements to the already well proven commercial aerial photography. In some instances these photos may well serve as completely workable substitutes. With the use of the light airplane and the 35mm. camera he can make his own type-study aerial photographs—precisely the photos he wants, when he wants them, and at extremely low unit cost. By such means he can greatly broaden the scope of his field source materials.

One of the most important single gains certainly is the opportunity to work at all times with completely up-to-the-minute aerial photographic data—photographs which the geographer himself may "shoot" in the morning and actually use for study purposes later the same day. Another advantage is the absolute control which the

geographer has over photographic elements like subject, composition, scale, and angle of view. The ultra-flexible light plane makes possible numerous photographs of any particular objective, from any angle, from any direction, and on any scale desired. High obliques, low obliques, or verticals may be made from roof-top levels or from mile-high heights—and all can be made in a single flight lasting only an hour or two.

Possibly the greatest advantage to the geographer lies in the simple fact that these type-study aerial photographs may be made not only in ordinary black and white, but also in full natural color. This latter factor is of great importance, for, although the superiority of full color is unquestioned, no color aerial photographs are available through normal commercial channels.

CHOICE OF TOOLS AND ACCESSORIES

Many types of airplanes *can* be used in geographic field work, but the inherent characteristics of some strongly suggest their choice over others. The qualities most desirable in an airplane for this purpose are slow cruising speeds, stability and smoothness in flight, ease of operation, wide angle ground visibility, and low operational cost. These qualities are found combined in varying degrees in several available makes in the so-called "light plane" class, like those that are to be found on the small local airports which serve almost every neighborhood in the country today. They may be rented at relatively standard prices of six to nine dollars per hour if flown solo by the investigator himself, or they may be rented with a licensed pilot for nine to twelve dollars per hour. The writer has usually flown alone and has used primarily the Cub Trainer, the Aeronca Trainer, and the Luscombe, with full satisfaction in each instance.

Several types of cameras *can* be used in making this personalized aerial photography, but, like the airplane, certain types are preferable. The qualities generally most desirable in a camera for this work are low initial cost, low film cost, lightness of weight, and simplicity of operation. The ordinary 35mm. camera best fulfills these various requirements and also gives very satisfactory photographic results. The writer has used mainly the inexpensive Argus 35mm. camera and, to lesser extent, the Kodak and the Leica 35mm. cameras, with exceptionally good results under extremely varied weather conditions.

Film for use in this work is identical with the type and quality used in conventional ground photography. In black and white film, there is a wide range of choice, but the film selected might well be fine-grained, relatively fast, and capable of considerable tonal contrast. Good results have been obtained with Ansco Panchromatic Supreme film. In color film, the choice is limited to two brands, Eastman Kodachrome film and Ansco Color film. Either may be used with assured results in 35mm. cameras and each is a standard product available in "20 exposure magazines" at most film supply stores.

Film exposure time for aerial photo work up to a few thousand feet altitude does not differ appreciably from that required at ground levels for comparable landscapes under similar conditions. But, for very best results, the use of a reliable

light meter in exactly the same manner as on the ground is strongly recommended. Special care should be taken to keep exposure time as short as possible, preferably not longer than 1/100 second. If exposure time is unduly long, i.e., 1/50 or 1/25 second, the resultant picture may show some degree of "subject fracture" due to engine vibration. Since the camera is held in the hands, and not attached to the plane by a fixed mount, the greatest danger of vibration may be almost completely alleviated by idling the engine and effecting a shallow glide for the necessary exposure time.

Haze conditions are usually present to some degree in nearly all localities, and may largely be rectified by the use of a haze filter specified for the particular film.

SOME SUGGESTED PROCEDURES AND EXPEDIENCIES

Based on the results of numerous and continuing experiments, certain procedures and expediencies relative to the making and eventual use of type-study aerial photographs have tentatively been adopted.

Most general-study photos are made at about eight hundred feet altitude above mean ground level with the 35mm. camera. From this height good photographic definition, extensive ground coverage, and large scale are all obtained in most satisfactory balance. Special purpose photos can be made with this camera ranging from ground levels to altitudes of several thousand feet, but at either extreme certain qualities must be sacrificed for the improvement of others.

The greater number of general-study photos are made as low obliques (20° to 40° from the perpendicular), for the dual reason that they lend themselves better to comparative interpretation and encompass considerably larger ground areas than do true vertical photos. Also, such photos are all oriented by the compass toward the north. This assures uniform lighting and exposures, as well as uniformity of shadow patterns. This greatly facilitates subsequent location of the photo on base maps and mosaics for study and data plotting purposes.

SOME SUGGESTED UTILIZATION TECHNIQUES

There are several practical methods of utilizing these type-study aerial photos, each method being conditioned somewhat by the type of camera and type of film used. If black and white film and the 35mm. camera are employed, the negatives can readily be used to make photoprint enlargements in a wide range of sizes—these closely resemble commercial aerial photographs in form—for study purposes and for published illustrations. Or, the negatives can be converted into slides and used for direct visual study with any ordinary 35mm. slide projector and screen. Examples of photoprint enlargements are shown in Figures 1 through 8.

If color film is used in the 35mm. camera, the best and least expensive method is to employ the standard color-transparency slides with any 35mm. slide projector and screen for direct visual study. It has been found that the projection method of color slides offers unusual study possibilities, considerable flexibility in photo selection, wide choice of viewing scale, and almost unlimited detail. Color film

and the projection method have been used exclusively for all except the preliminary stages of experimental work with type-study aerial photography, and with excellent results.

CONCLUSION

The general concept of geographic field work in the past has been to make detailed ground studies and surveys of all the features of an area. Now, with the slow, low-flying light airplane and the 35mm. camera as new field tools, it is possible to simplify and greatly expedite previous procedure. For, with only a minimum of preliminary field survey control, one can quickly and accurately prepare pattern and distribution sketch maps, in requisite detail, from personal aerial observations and from supplemental type-study aerial photography. In such fashion, the necessarily slow and tedious ground work heretofore necessary can be appreciably reduced.

This paper has been prepared solely for the purpose of setting forth some preliminary ideas and results relative to the use of the light airplane and the 35 mm. camera in a new role. Experiments are being continued and it is hoped that even more fruitful results can be obtained.

Fig. 1

VALLEY FLOOR AND MESA (TERRACE)

Santa Maria River in Foreground. Nipomo Mesa and Hills lie beyond mesa (terrace) bluff.

    Direction: N 20° E
    Altitude: 3000 feet; high oblique
    Weather: Scattered clouds at 2000 feet
    Location: Santa Maria Valley, California
    Date: September 1947
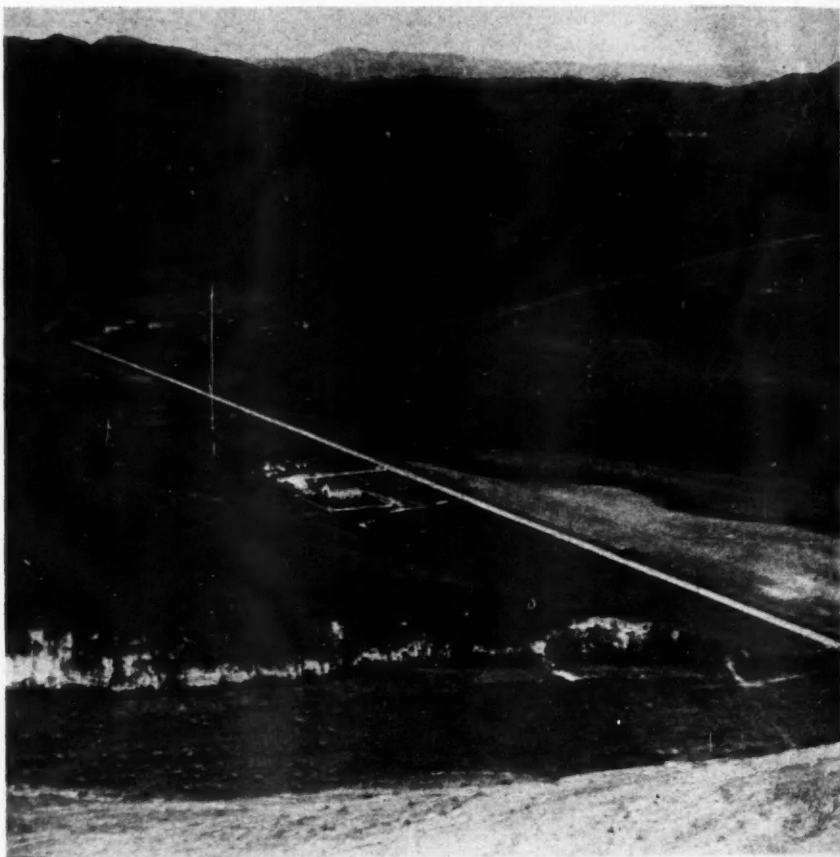
FIG. 2

TRIBUTARY VALLEY

Santa Maria flood channel and mesa (terrace) bluff in foreground.

Direction : N 45° E
Altitude : 800 feet ; high oblique
Weather : Heavy cloud overcast ; heavy haze
Location : Santa Maria Valley, California
Date :   March 1949

FIG. 3

EROSION ON NIPOMO MESA (TERRACE)

Santa Maria River flood channel in foreground and Nipomo Mesa (terrace) in background.

Direction : N 15° E
Altitude :   900 feet ; low oblique
Weather :   Clear sky ; light haze
Location :   Santa Maria Valley, California
Date :   October 1947

FIG. 4

DAIRY BARNS AND HERD

The adjoining fields are in irrigated alfalfa and vegetable crops.

Direction : N 50° W
Altitude :   700 feet ; low oblique
Weather :   Clear sky ; light haze
Location :   Santa Maria Valley, California
Date :   October 1947

FIG. 5

IRRIGATED VEGETABLE CROPS

Vegetable fields in foreground and Santa Maria River (dry) in background.

Direction : N 20° E
Altitude :   890 feet ; low oblique
Weather :   Clear sky ; heavy haze
Location :   Santa Maria Valley, California
Date :   October 1947

FIG. 6

TOWN OF GUADALUPE

Irrigated vegetable and flower-seed fields extend even into the town.

Direction : N 20° E
Altitude :   1000 feet ; low oblique
Weather :   Clear sky ; light haze
Location :   Santa Maria Valley, California
Date :   October 1947

FIG. 7

EAST SIDE OF TOWN OF GUADALUPE

Railroad yards in center foreground and flower-seed fields in background.

Direction: S 80° E
Altitude: 1000 feet; low oblique
Weather: Clear; light haze
Location: Santa Maria Valley, California
Date: October 1947

FIG. 8
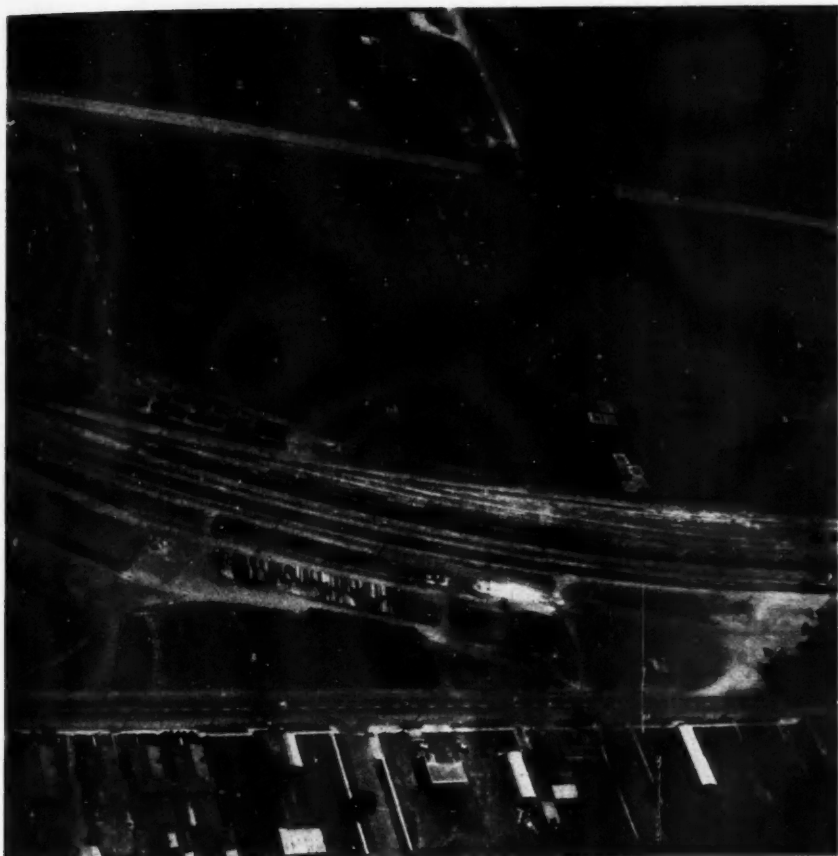
NORTH SIDE OF CITY OF SANTA MARIA

Direction : Due south
Altitude :   800 feet ; low oblique
Weather :   Heavy cloud overcast ; heavy haze
Location :   Santa Maria Valley, California
Date :   March 1949

A PHYSIOGNOMIC CLASSIFICATION OF VEGETATION

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I T is the task of biogeograhy to describe and explain the distribution of organisms on earth. The use of maps as basic tools is inevitable, but, so far, vegetation maps have contributed little to studies of a world wide character. It is no longer possible to investigate the vegetation of an area without considering that of the neighboring regions, of the whole continent, and, in fact, of the world. It has been shown repeatedly, as for instance by Meusel (1943) in his masterful presentation and by Küchler (1946) that comparative studies are fundamental, but existing vegetation maps do not at the present time permit detailed scientific comparisons of widely separated areas because there is at present no method of mapping vegetation which allows a comparative approach. The study of vegetation or plant sociology has shown great advances in the course of this century and yet it has proved inadequate to solve the basic problems of phytogeography. Even the most advanced system developed by plant sociologists, that of Braun-Blanquet (1928), is ungeographic. It therefore became necessary to devise a more natural classification of vegetation which avoids rigidity, permits world-wide comparisons, and is adapted to mapping. Such a classification is here submitted as a basis for further investigations, be they local or global in scope, and above all as a foundation for unified cartographic work. In developing this classification the author had the following principles constantly in mind: it must be applicable to all types of vegetation in all regions of the earth and must be adaptable to all map scales. Also, the system must not only be so flexible that it can fulfill the above conditions; it must be so clear and simple that all investigators can use it and produce the same results. Thus, two vegetation maps of contiguous areas compiled by different authors should fit together at their common margin. Unfortunately this occurs very rarely at the present time, largely because a universally applicable classification has not been developed.

In offering a new method of classifying and mapping the vegetation of the world, the author does not wish to minimize the efforts of those who have paved the way for the final development of a solution. Toward the end of the 19th century Grisebach (1884) first published his *Die Vegetation der Erde* and Schimper (1898) his *Pflanzengeographie auf physiologischer Grundlage*. The latter work has had a much enlarged and revised third edition in 1935 (Schimper-von Faber, 1935) and must be considered one of the corner stones of modern plant geography. Just before this, Du Rietz (1931) published his important work on life forms. Whereas all these men approached their problems primarily from a purely scientific point of view, there has been at work recently a growing number of men in various parts of the British tropics with an interest in the more immediate practical value of vegetation, especially from the viewpoint of forestry. Significant contributions

were made above all by Burtt Davy (1938), Champion (1936), Chipp (1926), Richards, Tansley and Watt (1940), and others. Valuable contributions are also being made by French and Belgian scientists in various parts of Africa.

The link between Schimper and these Englishmen is that they approach the study of vegetation in a manner altogether different from that of most plant sociologists. Their basis is *physiognomy*, the use of which was also the first and foremost adopted recommendation of the Botanical Institute of the Academy of Sciences of the U.S.S.R. (1935). Physiognomy has proved so successful and indeed can be supported on such obvious and logical grounds that it has been adopted here as the very framework of the new method of classifying the vegetation of the world. Logically all investigations of ecological or historical relations can only follow after the vegetation has been described just as it has been observed. To record the physiognomy is therefore the primary and fundamental step that has to precede all others.

First attempts to formulate and apply a physiognomic classification were published recently (Küchler, 1947, 1948). They have resulted in a most gratifying and encouraging correspondence with many who felt the need for such a system. The critical discussions and valuable contributions of many colleagues have helped greatly in making the new method more workable and it is here submitted in a more final form. The author is especially indebted to Dr. Pierre Dansereau of the Service de Biogéographie, Montreal, and to Dr. Donald B. Lawrence, editor of *Ecology*, for their tireless encouragement and many helpful suggestions.

In presenting vegetation on a map, it is necessary to show it in such a way that the reader can visualize the vegetation. In other words, the vegetation must be presented on the map in symbols that can readily be translated into appearance in the landscape.

Once physiognomy had been chosen as the basis of the new method, the next step was to find a way to translate the appearance of the vegetation into symbols that can be shown on a map. Here Wladimir Köppen pointed the way. His classification of climates (Köppen, 1931) has been applied over the whole world and, although the climate of any place is something very elusive, he has nevertheless succeeded in expressing its various aspects simply and clearly. As Köppen was much influenced by the distribution of vegetation when he formulated his system, it was not a very long step from his climatic classification to a classification of vegetation along similar lines. Köppen's classification of climates does not tell of the weather on a given day nor of secular climatic changes, and likewise the new method, here proposed, does not tell of the species of which the vegetation is composed nor of the successional stages of ecological development.

The physiognomic classification of vegetation resembles Köppen's classification in so far as it, too, uses letters and letter combinations (formulae) to designate the various classes of vegetation. Each type is, of course, physiognomic in character. The primary vegetation classes are expressed by capital letters and each of these can then be qualified by one or more small letters as the case may require.

The entire plant kingdom has been divided into two major sections: woody

plants and herbaceous plants. Woody vegetation is seemingly more varied in its appearance than non-woody or herbaceous vegetation. In accordance with physiognomy as the guiding principle, the woody vegetation is shown on the basis of whether it is evergreen or deciduous, broadleaf or needleleaf, or without leaves. This at once establishes five groups, each one with its particular capital letter to designate it on the map.

WOODY VEGETATION CLASSES:

B: evergreen broad-leaf: most plants have broad leaves in contrast to needles (see below) and are not bare (without green leaves) at any season. Example: forests of the equatorial lowland regions without a distinct dry season: northern New Guinea, and along the Amazon.

D: deciduous broad-leaf: plants have broad leaves as B, but periodically defoliate so that they carry no green leaves. The time during which the plants are bare may vary in length. Example: forests south of Lake Erie.

E: evergreen needle-leaf (coniferous): the term needle-leaf is here understood to apply to the typically needle-shaped leaves of such trees as pines, spruces, true cedars, and the like. It is also to include leaves that are more scale-like in appearance, such as the leaves of some cypresses, junipers, and conifers of the southern hemisphere. In fact, the letter E stands for all conifers excepting those mentioned in connection with the letter N. Examples: coniferous forests of western Washington and British Columbia, and much of the Taiga.

N: deciduous needle-leaf (coniferous): The term needle-leaf is here used as in E and the term deciduous is here used as in D. Example: larch forests of Siberia, especially east of the Yenisei.

O: leaves absent: this applies primarily to those plants which have chlorophyll in their stems such as the Euphorbia forests of East Africa or the Casuarina forests of New Caledonia, the arborescent cacti, and a number of desert shrubs.

HERBACEOUS VEGETATION CLASSES

The second group of capital letters is applied to the non-woody or herbaceous vegetation. It happens frequently that herbaceous types are decidedly seasonal in character. This is, of course, more true of some types than of others, but in any event, all herbaceous vegetation is always shown on a map as it appears in the landscape at the time of its fullest development. As in the case of woody vegetation, the herbaceous groups are divided according to their appearance in the landscape, their physiognomy. There are three classes.

G: graminoid: this term includes above all the grasses. To these are added all plants which are grasslike in appearance, even though they are not grasses in a strict botanical sense, such as sedges, reeds, cattails, and others. The bamboos, although members of the grass family, are not here included, as they are woody. Examples: the Pampa of Argentina (more especially in the province of Buenos Aires), the North American Prairie.

H: forbs: these are the many broad-leaf herbaceous plants, in contrast to the narrow-leaf graminoids. They are usually of the flowering type, but H also includes all non-epiphytic ferns except tree ferns. Examples: the Loma of Peru, or the ground cover of many forests.

L: lichens and mosses: only those which grow on the ground, i.e. which are not epiphytic are included here. Examples: sections of the Tundra.

This concludes the list of vegetation types which have been selected here as major classes, designated with capital letters. It is obvious that not all kinds of plants have been included in this scheme; for instance, there seems to be no place for bacteria or even fungi and others. However, these plants are not obvious in the physiognomy of the vegetation and can therefore justifiably be omitted. These classes are not evenly distributed over the earth, nor do they cover areas of equal size. B, D, and E are wide-spread and continuous. N occurs as a large formation only in the form of Siberian larch forests, but is nevertheless frequent locally in the Alps and much of northern North America, often in association with other conifers. The bald cypress (*Taxodium distichum*) and the recently discovered Metasequoia of west central China are also shown as N, but their occurrence is so limited that they can appear only on maps of a large scale. The letter O is even more restricted areally than N.

QUALIFIED CATEGORIES

A division of the world's vegetation into these eight classes is inadequate. For this reason a series of small letters has been introduced, of which one or more may be chosen to qualify further any one of the capital letters. These small letters are arranged in three groups. There may, of course, be no need to use letters of every group, and in any case, the number of letters used to describe a vegetation type depends largely on the scale of the map. The smaller the scale, the shorter may be the letter combinations or formulae. However, the list of small letters is sufficiently long and varied to describe the vegetation in detail, even though the scale of the map may be very large, and the required degree of accuracy exclude generalization.

Group I consists of five letters to designate the height of the vegetation, and also whether the woody plants occur in the landscape as trees or shrubs. As in the Köppen classification of climates, so here, too, it has been impossible to avoid the introduction of arbitrary delimitations. Whenever an arbitrary choice is made, it is at once open to criticism. All choices here are made in a manner which seems the most useful to the author and their number is so small as not to endanger the system as a whole. The letters indicating the height of the vegetation have different values according to whether they refer to woody or herbaceous vegetation.

Group I.

t: tall; average minimum height of trees: 25 meters.

    average minimum height of herbaceous plants: 2 meters

m: medium high; average height of trees: 10–25 meters.

average height of herbaceous plants: ½–2 meters.

l: low; average maximum height of trees: 10 meters.

average maximum height of herbaceous plants: ½ meter.

s: shrubs.   Minimum height: 1 meter.

z: dwarf shrubs.   Maximum height: 1 meter.

All capital letters referring to woody vegetation imply tree growth. If the vegetation does not consist of trees, the capital letters must be accompanied by an "s" or a "z". Thus the letter B stands for a vegetation of broadleaf evergreen trees. Bs indicates a vegetation of broadleaf evergreen shrubs with an average height of more than one meter. Finally, Bz states that the vegetation consists of broadleaf evergreen dwarf shrubs, which do not generally exceed one meter in height. If the vegetation consists of both trees and shrubs of the same class, the height of the trees should be given to avoid confusion: Bms. This formula shows that the vegetation consists of a forest of broadleaf evergreen trees of medium height (10–25 m) with an understory of broadleaf evergreen shrubs which generally exceed one meter in height.

In some regions, especially in the tropics, large areas are covered with a vegetation which consists of a transition between shrubs and trees. It is, in fact, often difficult to determine whether one is confronted with trees or shrubs. To avoid confusion, D or Ds should be used only when the vegetation is composed of what can be clearly identified as trees or as shrubs respectively. In all doubtful cases, as in the transitions, it is best to represent the low trees and the shrubs as both being present, thus: Dls. .

Group II of five small letters refers to the spacing of the plants in the landscape. In this group it is not practical to use arbitrary numerical values and the terms are therefore flexible.

Group II:

c: this letter can often be omitted if the map scale is small. It implies a continuous dense growth, but in view of the other letters of Group II, it may be assumed that a vegetation type is continuous unless it is accompanied by any one of the other letters of this group. Where vegetation types of varying density occur together, a "c" should be used to bring out the contrasts with less dense stands.

i: plants are standing close enough together to give the appearance of a continuous growth, at least from a distance. However, the individual plants are spaced so far apart that they usually do not touch. The spacing varies somewhat according to what plants are involved. Spruces and others of class E need not be very far apart before the ground between them is flooded with sunlight while the greater number of trees in class B may be much more widely spaced before the canopy is broken. Among the herbaceous plants the letter "i" is especially useful when referring to bunch grasses.

p: when used in connection with woody vegetation this letter indicates that the trees or shrubs grow singly or in groves as in so-called parklands or in savannas. It implies disconnected patches when referring to herbaceous vegetation.

r: indicates a type of vegetation which is rare, but at the same time so conspicuous
   in the landscape that it cannot be ignored without rendering the description in-
   adequate.   It may, for instance, be used for occasional shrubs on the margin of
   a desert (Dsr or Osr).   It may, just as well, refer to a type of vegetation
   which is associated with another type of greater continuity.   Thus, occasional
   widely scattered tall palms may rise out of continuous cover of broadleaf ever-
   green shrubs (Bsc. utr).

b: the landscape is barren and the vegetation is largely or entirely absent.

These groups of small letters are finally supplemented by another set of small
letters which show special peculiarities of the vegetation.   Such particular fea-
tures can here be admitted only if they are physiognomic in character and they have
been selected strictly on this basis.   If it seems that floristic aspects are introduced,
then this is purely coincidental.   From the point of view of taxonomy the selec-
tion is entirely illogical, but then, it is not systematics but physiognomy that guides
this choice.   This last group contains eight small letters all of which refer to the con-
spicuous presence of the features in question.   Unless these features are abundant,
their letters do not appear in the formula on the map.

Group III.

e: epiphytes.

j: lianas.   The term liana is here used for all woody plants that climb up trees or
   shrubs.   Annual herbaceous creepers such as the morning glory (*Convolvulus
   arvensis*) do not generally play a sufficiently significant role in the physiognomy
   of the vegetation to be included here; they belong to H.

k: succulents.

q: cushion plants.   Low plants with an exceedingly large number of branches,
   forming a very dense cushionlike growth.   Common in high altitudes and also
   in the lower altitudes of the higher latitudes (especially in the Southern hemi-
   sphere), as for instance *Draba alpina, Nierembergia patagonica, Cruckshank-
   sia glacialis*.

u: palms.

v: bamboos.

w: aquatic vegetation.   There is, of course, a great variety of plant life growing
   in water, and from a purely botanical point of view, a whole series of letters
   might be introduced.   However, for the purpose of mapping, the vegetation
   of water bodies is insignificant compared with that on land and while it can-
   not be ignored entirely, it is adequate to indicate it by a small letter.   This
   includes all forms of aquatic plant life, whether submerged as *Sargassum*, partly
   floating like water lilies (*Nymphea alba*), or floating entirely as the duck weed
   (*Lemma minor*).   Plants which root under water but carry important parts
   above the surface (e.g. mangroves or reeds) are not included here.

y: tree ferns and tuft plants.   These latter are woody plants usually with a stocky
   trunk and carrying a tuft of leaves at their top.   They are especially common
   in the high altitudes of the tropics, and in some arid regions.   Examples of tuft

plants include *Espeletia hartwegiana* and *Senecio keniodendron*.

METHOD OF APPLYING THE CLASSIFICATION

For a rapid survey it will be convenient to consult the tabular arrangement of all the letters and their respective meaning (Table 1).

TABLE 1

THE PHYSIOGNOMIC CLASSIFICATION OF VEGETATION

CAPITAL LETTERS.

Woody Vegetation:
- B: evergreen broadleaf
- D: deciduous broadleaf
- E: evergreen needleleaf (coniferous)
- N: deciduous needleleaf (coniferous)
- O: without leaves

Herbaceous Vegetation:
- G: graminoids
- H: forbs
- L: lichens & mosses

SMALL LETTERS.

Group I: Height:
- t: tall; minimum height of trees: 25 m.
  minimum height of herbaceous plants: 2m.
- m: medium tall; trees: 10–25 m.
  herbaceous plants: $\frac{1}{2}$-2 m.
- l: low; maximum height of trees: 10 m.
  maximum height of herbaceous plants: $\frac{1}{2}$ m.
- s: shrubs; minimum height: 1 m.
- z: dwarf shrubs; maximum height: 1 m.

Group II: Density
- c: continuous growth
- i: plants usually do not touch
- p: woody plants scattered singly or in groves
  herbaceous plants in disconnected patches
- r: rare, yet conspicuous
- b: barren; vegetation largely or entirely absent

Group III: Special Features.
- e: epiphytes
- j: lianas
- k: succulents
- q: cushion plants
- u: palms
- v: bamboos
- w: aquatic vegetation
- y: tree ferns & tuft plants

These capital and small letters are grouped together into formulae in such a way that each formula adequately describes the existing vegetation. In making up a formula, the most conspicuous type is always placed at the beginning. For instance, if the vegetation consists of deciduous oaks with grass covering the forest floor, the formula reads DG. If, on the other hand, the vegetation is a grassland

over which oaks are scattered thinly, the formula is reversed, and the grasses are put ahead of the trees; the formula changes to GDp. These formulae can then both be made more precise by referring to the height of the trees and of the grass if that should be desirable.

The small letters are used to qualify the capital letters. Each capital has its own small letters and therefore must be followed by them immediately. If there is more than one capital letter in the formula, each will have its small letters independently of the other. For instance: DmG implies that the broadleaf deciduous forest is of medium stature, but the formula says nothing about the height of the grass that grows in the forest. If the formula reads: DGm, the implication is that in a broadleaf deciduous forest (height not given) there grows a ground cover of medium high grass. If the height of both the trees and the grass is wanted, then both must be given separately: DmGm, DlGt, DtGl, or whatever the case may be.

If a series of small letters is to be given, then they follow one another in the sequence of the groups. This is to say that the small letters of Group I are placed immediately behind the capital letters; they are followed by letters of group II, while the letters of group III come last. However, this arrangement is valid for each capital letter separately when there is more than one capital letter in the formula.

In some instances, especially when the formulae are long, there may develop a difficulty in distinguishing individual aspects of the vegetation. In order to avoid a misinterpretation of the formula, a point is placed between the groups of letters which belong together. For instance H. G. Champion has described a deciduous forest in India (Champion, 1936) which consists of several stories and associated features. It has the formula Dmls.jr.Gp which requires the placing of points. This forest consists evidently of deciduous trees of medium height and also a tier of deciduous trees of low stature. In addition, there is a layer of deciduous shrubs. All are broadleaf. In this deciduous growth there occur lianas which are not frequent but nevertheless so conspicuous that they cannot be ignored. Finally there are patches of grass for which no height is given. In this formula the lianas have to be separated by a point from the deciduous trees and shrubs because the "r" refers only to the lianas. Without the point the "r" might be taken to apply to all woody plants. The second point in the formula is not necessary and may well be omitted. It is inserted in this long formula to set off more clearly the grass from the other growth forms.

The number of letters used in a formula depends on the available information and the scale of the map. Most maps are of such a small scale that the information on them is generalized. Accurate and complete maps must have a scale of 1:25,000 or larger. If the scale is smaller, generalization is inevitable unless the vegetation is very monotonous over large areas. The smaller the scale and the greater the degree of generalization, the shorter may be the formulae.

The formulae should also be kept short if the purpose of the map does not require a great amount of detail. On the other hand, when there is need for exact in-

formation the map scale must always be kept very large, so that it is possible to permit long formulae wherever these are necessary to describe the vegetation accurately.

A few examples may here be in order. If one climbs a mountain in all except the highest latitudes, the vegetation changes very distinctly with increasing altitude. At the foot of the mountain the vegetation may consist of broadleaf deciduous forests and the formula reads D. Higher up conifers rapidly increase in number and the formula changes first to DE, then to ED. Above this mixed forest the conifers are likely to occur in pure stands and the formula changes to E. It may be well to mark such a forest with Ec because, not much higher, the forest will begin to thin out with a formula change to Ei. At timberline the vegetation changes radically. At this elevation climatic features may force many conifers to grow prostrate on the ground and less continuously than below timberline; the formula then reads Elsp. Grasses or sedges will appear to change the formula to ElspGl. Still higher up the grass dominates the landscape and is placed at the head of the formula: GlEsp. Above this the grass reigns supreme: Glc; but at last it, too, begins to give way and is followed first by Glp and finally by Glb which is nothing but a few lonely bunches of low grass in an otherwise barren environment. Frequently forbs and dwarf shrubs or other life forms become prominent above timberline and the formulae must then be altered correspondingly.

The Taiga appears on a small scale map as E. But as the map scale grows and the areas shown shrink, this one-letter formula may change considerably. Thus, it may grow to EDr or to EmDlr. At its southern margin the Taiga usually changes to ED and later to DE and passes through a parkland aspect into a grassland. In this case the sequence of formulas is likely to be somewhat like this: E–ED–DEGp–GDp–G.

The great broadleaf evergreen forests of tropical lowlands with several stories may have a formula like this: Btmlsej. If it is not desired to show the stratification of such a forest, the formula can be reduced to Btej. In some cases, and especially on large scale maps, a "u" might be added.

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PRESENT DISTRIBUTION AND AFFINITIES
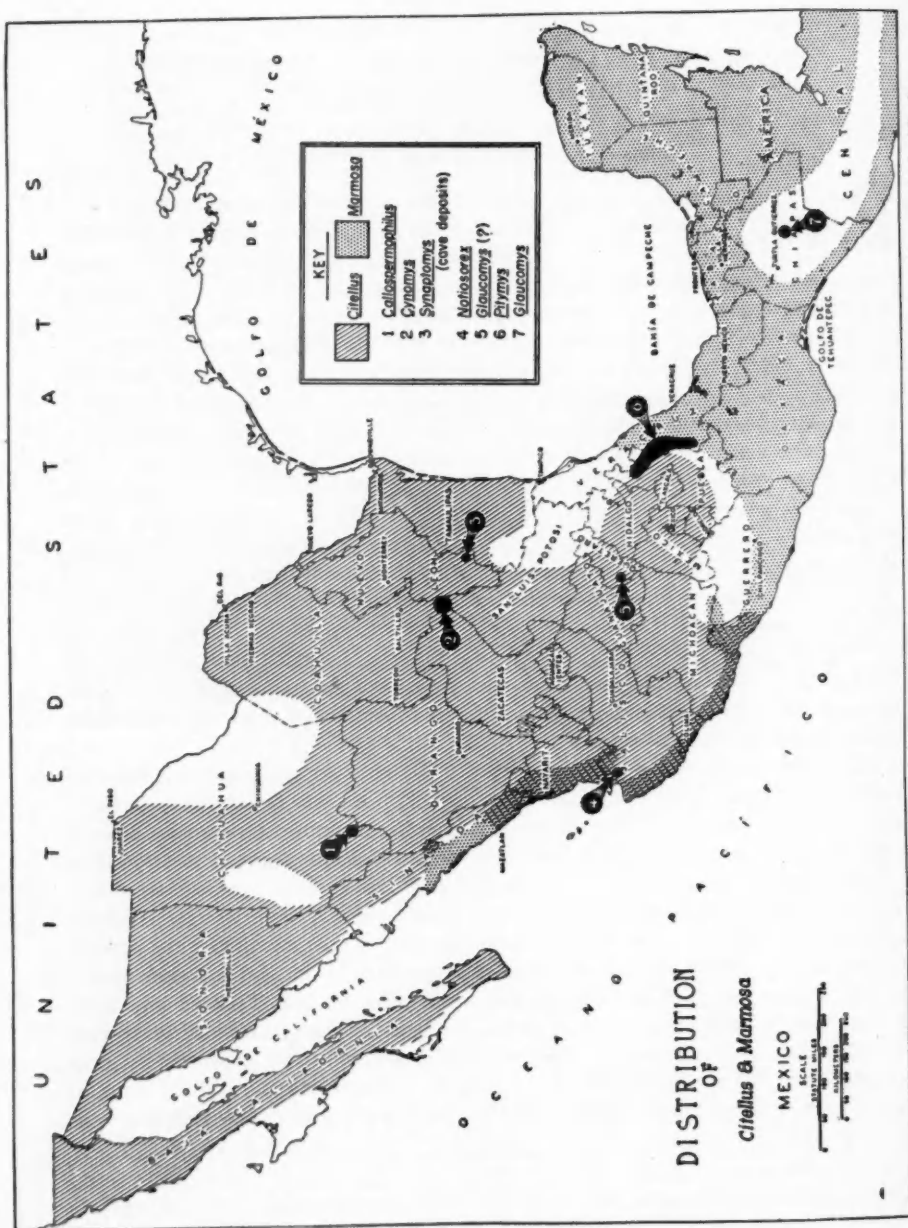## OF MEXICAN MAMMALS*

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PHYSIOGRAPHICALLY, the land mass of Mexico consists of a mountain and plateau area and a low coastal area Each of these is occupied by a somewhat distinct mammalian fauna. There are certain mammal kinds that overlap these areas in their distributional patterns, but this is to be expected. The mountain and plateau area (including northern coastal areas) is inhabited principally by northern mammals. The other, tropical and subtropical, chiefly lowland and coastal, is occupied primarily by mammals with southern affinities. The areas are fairly well defined by the geographic ranges of the two genera—*Citellus* (ground squirrels), representing the northern element, and *Marmosa* (murine opossums), representing the southern group (Fig. 1). If we plot distributions, on the generic level, of the eighty-seven genera of non-flying land mammals known from Mexico, we find those of thirty-two genera falling within that outlined for *Citellus* and twenty-nine within that outlined for *Marmosa*. Twenty-six genera have geographic ranges that overlap and partially fill each of the two major areas, and are not confined within either one. These areas can be, and have been, further subdivided into fairly natural units. The northwest desert (Sonora and Baja California), the northeast coast, and the Yucatan peninsula, to mention the most obvious, are fairly distinct areas, but it is not the purpose in the present paper to go beyond the major divisions. I shall be concerned primarily with affinities in a broad sense—affinities with the mammalian faunas of the Americas.

To review briefly the geological history of North, Central, and South America from early Tertiary times, we know that mammals reached South America probably in the pre-Tertiary. The northern and southern continents were then isolated until late Tertiary. During this period of isolation, South America developed its perculiar mammalian fauna. A quite different fauna was evolving in North America. When land connections were again established, there was an extension of geographic range of certain South American species northward over the isthmus and of certain North American species southward. It was not an *exchange* of faunas, but an *addition* to each by the other. During late Tertiary and early Quarternary, some of the South American elements gradually extended northward where habitats and other environmental conditions permitted. Subsequently, during glaciation, the northern faunas were pushed southward and undoubtedly some, or all, of the invaders from South America retreated again. The lemming vole

Fig. 1.—Distribution of ground squirrels (*Citellus*), murine opossums (*Marmosa*), and relict species of mammals in Mexico.

(*Synaptomys*), now a boreal or sub-boreal species, occurred as far south as Nuevo Leon (Cushing, 1945). As the glaciers retreated northward there was again a northward shift of faunas—a shift of both northern and southern species. This last shift is probably still in progress.

With the last shift northward, many of the temperate climate mammals remained in the mountains and on the high central plateau of Mexico. A few genera and species probably evolved there, some remaining as endemics and others spreading northward and/or southward. In at least five genera (*Notiosorex, Callospermophilus, Cynomys, Glaucomys,* and *Pitymys*) relict populations, now completely isolated from other members of the genus, were able to persist to the present time (Fig. 1). These are all genera with northern affinities. I am not aware of a single southern relict species that persisted in the north. The porcupine (*Erethizon*) apparently moved north with the northern fauna after the retreat of the glaciers, but this is not comparable to the relict species left in the south.

In speaking of northern and southern affinities, it is meant that the same kinds, at least members of the same genus, are found to the north or south today. It does not necessarily imply origins. When we compare the present day mammalian fauna of Mexico with that of northern North America and with that of Central and South America, we are able to break it down into three main categories, i.e., 1) mammals with relationships to the north, 2) those with relationships to the south, and 3) those which apparently have had their own development in Mexico and show no very close connection with northern or southern groups.

If the total mammalian fauna is considered, those kinds (fifty-seven genera) with southern affinities predominate. The bats, being tropical for the most part, throw the weight toward southern kinds. By excluding the bats, and analyzing the non-flying land mammals, we get the following picture (Table I) : forty-three genera with northern affinities, twenty-seven with southern, and seventeen that are probably endemic to Mexico. The balance swings from predominantly southern to northern in total taxonomic relationships. There still remains a substantial Mexican element, indicating that Mexico proper has been a dynamic differentiation area for mammals. This reflects the great diversity of ecologic conditions to be found there today.

The marsupials, known from as far back as Upper Cretaceous in North America, are represented by four genera. The common opossum (*Didelphis*) is found both to the north and south; it is here considered that Mexico and Central America is where it has had its greatest development. Although not strictly Mexican, I prefer to place it in this category. The other marsupials, the murine opossum (*Marmosa*) and the woolly opossums (*Philander* and *Caluromys*), are definitely southern in their present day relationships.

The insectivores are represented by five genera, all of which are quite definitely northern in their affinities, past and present. They are found, in Mexico, chiefly in the mountains and on the high tableland. Shrews of the genus *Cryptotis* have diversified markedly more in Mexico and Central America, with more than twenty kinds, than they have in the northern part of their range where but two kinds are known. *Notiosorex* has a relict population (Fig. 1).

TABLE I

DISTRIBUTION AND AFFINITIES OF GENERA OF MAMMALS IN MEXICO

Genus	Distribution				Affinities			
	Northwestern Arid	Mountain and Plateau	Southern Tropical	Northeast Coast	Southern Relicts	Northern	Southern	Endemic
Didelphis		X	X					X
Marmosa			X				X	
Philander			X				X	
Caluromys			X				X	
Scapanus		X				X		
Scalopus				X		X		
Sorex		X			?	X		
Cryptotis		X			X	X?		?
Notiosorex		X			X	X		
Ursus		X				X		
Procyon		X		X		X		
Nasua		X	X				X	
Potos			X				X	
Jentinkia			X				X	
Bassariscus	X	X	X		?		?	X?
Mustela	X	X	X	X		X		
Tayra			X				X	
Lutra		X	X			X		
Grison			X				X	
Spilogale	X	X	X	X		X		
Mephitis	X	X	X	X		X		
Conepatus		X	X				X	
Taxidea	X	X				X		
Vulpes	X					X		
Urocyon	X	X	X	X		X		
Canis	X	X	X	X		X		
Felis	X	X	X	X		X?	?	
Lynx	X	X				X		
Alouatta			X				X	
Ateles			X				X	
Citellus	X	X				X		
Callospermophilus		X			X	X		
Ammospermophilus	X				X	X		
Cynomys		X				X		
Eutamias		X				X		
Tamiasciurus		X				X		
Sciurus		X	X			X		
Glaucomys		X	X		X	X		
Thomomys	X	X				X?		?
Geomys		X		X		X		
Pappogeomys			X					X
Cratogeomys		X						X
Orthogeomys			X					X
Heterogeomys			X					X
Zygogeomys		X						X
Heteromys			X					X
Liomys		X	X	X				
Perognathus	X	X				X		
Dipodomys	X	X				X		

TABLE 1 (*Continued*)

Genus	Distribution				Affinities			
	Northwestern Arid	Mountain and Plateau	Southern Tropical	Northeast Coast	Southern Relics	Northern	Southern	Endemic
Castor	X					X		
Onychomys	X	X				X		
Reithrodontomys	X	X	X	X		?	?	X
Baiomys	X	X	X	X				X
Peromyscus	X	X	X	X		X?		?
Oryzomys	X	X	X	X			X	
Tylomys			X				X	
Ototylomys			X				X	
Otonyctomys			X				?	X?
Rheomys			X				X	
Nyctomys			X				X	
Sigmodon	X	X	X	X		?		X?
Scotinomys			X				X	
Neotomodon		X				?		X?
Nelsonia		X				?		X?
Teanopus	X					X?		?
Neotoma	X	X	X			X		?
Hodomys			X			X?		?
Xenomys			X			?		X?
Microtus		X				X		
Pitymys			X		X	X		
Ondatra	X					X		
Coendou			X				X	
Dasyprocta			X				X	
Cuniculus			X				X	
Lepus	X	X				X		
Sylvilagus	X	X	X	X		X		
Romerolagus		X				?		X?
Pecari	X	X	X				X	
Tayassu			X				X	
Odocoileus	X	X	X			X		
Mazama			X				X	
Antilocapra	X					X		
Ovis	X	X				X		
Tapirella			X				X	
Cyclopes			X				X	
Tamandua			X				X	
Dasypus		X	X	X			X	

The carnivores, northern in origin, are still predominantly northern in distribution (twelve genera, *Ursus, Procyon, Mustela, Lutra, Spilogale, Mephitis, Taxidea, Vulpes, Urocyon, Canis, Felis,* and *Lynx*), but with a fairly strong southern influence (six genera, *Nasua, Potos, Jentinkia, Tayra, Grison,* and *Conepatus*). The ring-tailed cat (*Bassariscus*) is the only one that might be placed in the Mexican category, however, it ranges north to Oregon along the Pacific coast. The genus *Mustela*, nearly world-wide in distribution, has, in general, northern rather than southern affinities, and *Procyon, Spilogale,* and *Urocyon* are somewhat doubtful.

They might be placed in the Mexican category quite as properly as with the northern group. *Lutra* has a South American representative, but I believe it is best considered a northern animal.

The primates, excluding man, are represented by two genera (*Alouatta* and *Ateles*), both tropical, with South American affinities.

The rodents constitute a large and varied group. The squirrels, Sciuridea, all have northern affinities. There are tree squirrels (*Sciurus*) in South America, but the family Sciuridea is primarily northern. *Cynomys, Callospermophilus,* and *Glaucomys* are represented by relict populations. The pocket gophers, Geomyidae, have five genera (*Pappogeomys, Cratogeomys, Orthogeomys, Heterogeomys,* and *Zygogeomys*) that may be considered Mexican and two (*Thomomys* and *Geomys*) which possibly have northern affinities. The family as a whole, however, has had its greatest development in Mexico and probably should be considered primarily Mexican in relationships. The pocket mice and pocket rats, Heteromyidae, are divided with two doubtfully northern (*Perognathus* and *Dipodomys*) and two Mexican (*Heteromys* and *Liomys*) representatives. Here, as in the Geomyidae, the greatest development has been in Mexico. The beaver, Castoridae, with one genus (*Castor*), is northern, both in ancestral and present day relationships. The Cricetidae (principally new world rats and mice), although probably northern in origin, have four northern (*Onychomys, Microtus, Pitymys,* and *Ondatra*), five southern (*Tylomys, Ototylomys, Rheomys, Nyctomys,* and *Scotinomys*), and eleven genera (*Reithrodontomys, Baiomys, Peromyscus, Oryzomys, Sigmodon, Neotomodon, Nelsonia, Teanopus, Neotoma, Hodomys,* and *Xenomys*) that are chiefly Mexican in distribution. Two of the above, *Teanopus* and *Hodomys,* are probably subgenera of *Neotoma.* Most of these range beyond the boundaries of Mexico, but all are characteristically Mexican and each shows its greatest diversification in Mexico. *Pitymys* is represented by a relict population. The hystricomorph rodents all had their early development in South America and are emigrants from that continent. Their present relationships are with the South American fauna. Summing up the rodents as a whole, there are twenty-one genera with northern affinities, nine with southern, and fourteen that are chiefly Mexican, judged from present day faunas.

In the lagomorphs (rabbits and hares), the two genera *Lepus* and *Sylvilagus* are northern and the one genus *Romerolagus* is strictly Mexican, although its remote ancestors were probably northern in distribution. *Sylvilagus* goes into South America, but it is chiefly northern in distribution.

The artiodactyls are divided with three northern and three southern genera. The two kinds of peccaries (*Pecari* and *Tayassu*) and the brocket (*Mazama*) are South American elements whereas the deer (*Odocoileus*), pronghorn (*Antilocapra*), and bighorn (*Ovis*) are definitely northern animals. All probably had their origins in the north, but the peccaries and the brocket have developed in the south.

The perissodactyls are represented only by the tapir, a tropical South American product with a remote northern ancestry.

Three genera of Xenarthra (*Cyclopes, Tamandua,* and *Dasypus*) are again emi-

grants from South America and have their affinities with that fauna.

When we study the detailed distribution of the various kinds, we find that the northern elements and many of the Mexican elements occupy the cordilleras and tableland of Mexico while the southern elements are more likely to occur in the low tropical areas. This is not startling—it is what we should expect. Climate, soil, and vegetation definitely influence the distribution of mammal kinds. Wherever we find similar vegetation types, even though the species of plants are different, we may expect to find similar mammal types. The high plateau of Michoacan, with its pine-oak forests, and the northeastern part of the United States, with mixed hardwood and pine forests, have many species that are either the same or closely related. A precise comparison of the mammal fauna of the higher parts of Michoacan (excluding the Tierra Caliente) with that of an area as remote as Michigan reveals several similarities. Our knowledge of the mammals of Michoacan is yet far from complete, but, with the exception of the bats, we have a fairly good idea of the genera found there. Exclusive of bats, there are thirty-six genera of recent wild land mammals known from Michigan and thirty-four (possibly a few more) from the tableland and mountains of Michoacan. The two faunas are of nearly equal size as regards numbers of kinds. Seventeen genera and nine species of non-flying land mammals are common to the two areas. There are nineteen genera in Michigan that are not found in Michoacan and seventeen in the latter state that do not occur in Michigan. If we apply the formula $\frac{100\,C}{N1}$ for taxonomic resemblance (Simpson, 1947), we obtain the measure 50. This means that 50 per cent of the smaller (Michoacan) fauna is common to the larger (Michigan) fauna. (In this case genera are used as units.)

The measure of taxonomic resemblance that one obtains between two faunas depends on the units (categories) employed in the comparison. The larger the category the greater will be the resemblance (Simpson, 1947). If we drop to the species level, the measure is 21.4. This is considerably less than one obtains in comparing Michigan with California (86 for genera and 43 for species), an east-west comparison on the same basis, and approximately the same distances apart.

The large segment of northern genera and species found in the mountain and plateau area of Mexico today is responsible for the taxonomic resemblance between that area and northern North America. It is quite evident that most of the Mexican non-flying land mammalian fauna developed in Mexico or to the north. An important addition has been made from South America, but many of the peculiar genera that evolved in South America did not cross the isthmus. Perhaps habitat conditions were not suitable and served as a barrier to them.

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HERPETOGENY IN MEXICO AND GUATEMALA*

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THE course of development of the herpetofauna of the present day—that is to say, the herpetogeny—of Mexico and Guatemala is rather obscurely indicated. It is a remarkable fact that from the entire area mentioned no fossil amphibians and very few fossil reptiles are known, other than Pleistocene remains generally conspecific with living forms. Accordingly all discussion of herpetogeny in the prescribed area must be based upon less direct indications: (1) phylogenies of groups sufficiently well known and studied to be reasonably useful; (2) fossil remains in adjacent areas; (3) paleophysiography, especially as indicated by Schuchert (1935); (4) herpetogenies of limited areas which have been well studied, as for example Sonora (Bogert and Oliver, 1945); (5) modern physiography and herpesian[1] life areas; and (6) implications of studies on other animals and on plants.

Since the classes of reptiles and amphibians are much more ancient than those of mammals or birds, the impression is easily obtained that modern groups are equally ancient and, thus, have had a history of migration much different from that of more recent classes. On the contrary, modern groups of both reptiles and amphibians apparently flowered in the Cenozoic, as did mammals and birds, despite the fact that scattered remains are known from the Mesozoic. Thus it is not unreasonable if, as appears the case, the gross features of herpetogeny are closely correlated with those of mammalogeny and aviogeny.

Known herpesian phylogenies establish securely the fact that the Mexican and Guatemalan plateaux are populated preponderantly by primitive species. In groups thus represented it is remarkable that the living "primitive" forms are rarely, if ever, generalized in all respects. They are specialized in certain features, often rather highly. Radiating away from the Mexican and Guatemalan centers are forms representing various lines of specializations and stabilizations. Naturally phylogenetic trees thus almost invariably have their bases in the plateau area, and the branches directed away from that area.

Phylogenies of intrageneric groups indicate the great importance at the species and/or subspecies level of the Miocene-Pliocene portal at the Isthmus of Tehuan-

[1] The term *herpetological*, generally used in the same sense that *herpesian* is here used, actually means "the study of reptiles and amphibians." Although commonly used to mean "pertaining to reptiles and amphibians," etymologically the word *herpetological* does not convey that idea. A more appropriate word is *herpesian*, formed from the original Greek word *herpes*, applied specifically by common consent to reptiles and amphibians.

tepec. Mammalogists, more accustomed to correlation of that portal with at least the generic level, are inclined to regard the herpesian correlation with suspicion. Despite the fact that such correlation may be more popular than actual, the conclusion is unavoidable that all of the several phylogenies known do fit Schuchert's paleogeographic outline most remarkably.

It appears, accordingly, that herpesian phylogeny has proceeded at a more moderate, conservative pace than mammalian.

Discussion of herpetogeny in the area prescribed is perhaps best treated in three sections: (I) the basic pattern of migration; (II) the local pattern of dispersal; and (III) the present facies of distribution throughout the area.

I. BASIC PATTERN OF MIGRATION

Three major horofaunae[2] within the Americas are generally recognized in all vertebrate groups (Dunn, 1931; Mayr, 1946; Schmidt, 1946). These have been termed the South American (the earliest), Old Northern, and Holarctic (the latest). Mayr (1946) extends these to the Old World. His Pan-Tropical fauna is represented in the western hemisphere by the South American; his Pan-Boreal by the Holarctic; but no general name is applied to the fauna represented here by the Old Northern (which he calls North American), although its counterpart in the western hemisphere is called the Old World fauna.

All of these American horofaunae appear to be of northern derivation. The evidence is not conclusive for the earliest element, but there is little question that the later two were emigrants from the north and, ultimately, northwest.

The three horofaunae are as much a result of the existence of dispersal barriers as are modern faunal areas. The two most important barriers were the Central American and Aleutian oceanic portals. Climatic cycles undoubtedly played an important role in the total effect of the latter portal.

The Holarctic horofauna invaded North America no earlier than late Pliocene and subsequent times. Its dispersal was intimately correlated with glacial patterns (Schmidt, 1946), resulting in strange faunistic affinities only recently explained.

The South American horofaunae developed during the Eocene, Oligocene, and according to most authors, even early and middle Miocene, when South America was separated from North America by a Panamanian oceanic portal. During the time the South American horofauna was developing, obviously the Old Northern fauna was becoming distinct, adulterated though it was at intervals by trans-Aleutian immigration from Asia. There is and can be no real, hard and fast line between the North American and later horofaunae because their limits are more or less arbitrary and not well known. Yet it is quite possible to devise a more reasonable

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[2] The term *horofauna* is introduced for the concept of temporal faunae. The latter are faunae of similar *origin* (both temporal and zoogeographic), as opposed to faunae of the ordinary sense, of similar *position* (area of occupation). The term "faunal element" adopted by others for the same concept, is in certain cases ambiguous, inasmuch as it can reasonably be used in reference either to horofauna or to regional faunae. The term "paleofauna" is a hybrid (Greek and Latin), but otherwise acceptable.

means of limitation than has heretofore been accepted. I suggest that both the North American and South American periods of differentiation be regarded as ending with closure of the Panamanian portal; and all subsequent immigrations from Asia should be regarded as comprising a third fauna, which might be called the North American horofauna.[3]

TABLE 1

CHRONOLOGY OF THE AMERICAN HOROFAUNAE

Eras	Old Northern Horofauna	South American Horofauna	North American Horofauna
Eocene-Oligocene	nearly complete isolation (Aleutian and Panamanian portals), with 1 or 2 temporary breaks in the Aleutian portal	complete isolation (Panamanian Portal)	....
Miocene	loss of isolation (both Panamanian and Aleutian portals closed)	loss of isolation (Panamanian portal closed)	initiation with closure of Aleutian portal
Pliocene	continued as above	continued as above	interrupted but continued
Pleistocene	as above	as above	continued (as the *Holarctic* division)
Recent	as above	as above	interrupted (terminated?)

Chronology of these three major horofaunae is not easily agreed upon. According to Simpson (1947: 625) a fairly high degree of immigration into North America from Asia occurred in the entire Miocene era, dropping off sharply at its end. There was a minimum of immigration in late Oligocene. This chronology in arctic areas does not however correspond closely with that generally accepted for equatorial areas, for the North and South American continents were not reunited, according to paleogeographers, until the late Miocene, at a time when an extensive Aleutian faunal exchange was occurring. It is true that no correlation in time of existence of these two portals is necessary, but on the other hand it may be expected that depression of land and extensive ocean expanse are generally global phenomena, and that two given major portals such as these are more likely than not to be coexistent. There is evidence, in fact, that the teiid lizards (especially *Ameiva;* Smith and Laufe, 1946) apparently entered Central America from South America much earlier than Late Miocene times; I had independently concluded in the Late Oligocene or Early Miocene. If evidence from other groups bear out the teiid data, then we may conclude that the termination of the period of differentiation of the North American horofauna is the lower Oligocene, both at the north and at the south. In brief this chronology may be summarized as in Table 1.

[3] This usage of "North American" is not the same as Mayr's, which is as a substitute for Dunn's "Old Northern." The present "North American" includes part of Dunn's "Old Northern" (and thus part of Mayr's "North American," and all of Dunn's "Holarctic." The latter is, however, here regarded as a division of the North American horofauna.

II. THE LOCAL PATTERN OF DISPERSAL

Within Mexico and Guatemala the Old Northern element obviously should and does include a very large proportion of the herpetofauna of the area. Both countries are well within the area previously isolated to the north of the Panamanian portal. That the South American element is poorly represented is reasonably correlated with (1) the distance of that area from the portal, and (2) the retarding effect of (a) contrary population pressures and (b) adverse competition.

All students of the herpetofauna of Mexico and Guatemala have been impressed by its tremendous complexity. This is a general feature of all Central America. Obviously the complexity is a reflection of the complex topography, but actually in pointing out this fact the underlying reasons for this correlation are not expressed.

Three phenomena are of importance in the faunistic role played by this area. First, it was so situated as to act at certain times as a cul-de-sac for forms migrating southward and at other times as a cross-roads for forms migrating both northward and southward, peripheral wanderers from the large land masses of South and North America. Second, its geological history was such that parts of the area were isolated from time to time, allowing a multiplication of the fauna, in a fashion otherwise impossible, through differentiation and subsequent migrations. Third, large areas with extensive vertical ranges were available for preservation of forms which, prevented from horizontal migration in times of climatic change by population pressures, could persist by vertical migration. These three phenomena, in conjunction, account for the amazing variety of the fauna of that area, and provide a basis for considering the plateaus of Guatemala and Mexico as among the most important areas of secondary dispersal in the Western Hemisphere.

Possibly, in fact, these areas should be called primary centers of dispersal. Apparently, however, they received their original populations from the Eastern Hemisphere. Globally speaking, they are secondary centers; hemispherically speaking, they are primary centers on a par with the continent of South America.

Within Mexico and Guatemala, the plateaus obviously served as the important centers of dispersal, while the coasts served as the chief pathways by which immigrants arrived and emigrants departed. Perhaps it would be well to consider the two plateaus as a single center of dispersal, in a gross sense, including even the elevated areas south to Nicaragua. It is true, however, that to at least a lesser degree each plateau, separated from its mate by lowlands at the Isthmus of Tehuantepec (where in the lower Pliocene an oceanic portal existed), acted as an independent center of dispersal. I would be inclined to regard them separately as dispersal centers of tertiary order, and collectively as dispersal centers of secondary (global) order. The Guatemalan plateau, of course, is to be thought of in a physical not a political sense, including the plateau of Chiapas as well as that of the present countries of Guatemala and El Salvador.

The three phenomena of faunistic development have not been equally well treated. Schmidt (1943) has emphasized the importance of the *Cul-de-Sac Phenomenon*. Virtually all authors are agreed that the *Isolation Phenomenon* also plays an im-

portant role. But the importance of the *Montane Phenomenon,* while touched upon by some authors, has never been duly stressed.

It is obvious that, in the normal expansion of a population, once barriers are reached on all sides, expansion ceases, until some mutant appears which thrives in a bordering territory. If however climatic changes are occurring, temperature and allied barriers are on the move, and likewise the population is on the move. The animals, in effect, seek to remain under the same conditions, although in following climatic combinations they may well be, and are, subjected to changes in other environmental conditions that in turn produce changes in the animals themselves.

Let us follow the animals during a period of increasing warmth on the earth's surface. Those on flat lands will obviously migrate in most directions—north, east, west and, to a lesser degree, south. Descendants in the original area inhabited cannot, obviously, migrate horizontally because of a population barrier, but if mountains are available they can and do migrate vertically.

In the climatic cycle a period of increasing cold eventually follows. Animals at the north cannot retreat, because of population pressure; they either differentiate to resist the cold or (as in most cases by far) they become extinct. Those which migrated to the east and west must suffer a like fate, unless they have entered a territory from which they can again migrate southward. Those which have migrated vertically at the original area of dispersal or anywhere else along the path of horizontal migration are preserved at progressively lower levels as the climate becomes cooler. At length the original form or direct descendants thereof are found preserved only (1) in new cul-de-sacs, and (2) around elevated areas, often in cul-de-sacs.

As the warm phase of the cycle returns, obviously the mountain ranges and cul-de-sacs—and of course especially the mountains of cul-de-sacs—again serve as centers of dispersal. With repetition of the cycle the elevated areas assume a role of major importance as on the one hand a place of refuge and on the other as a center of dispersal for any given group of animals. Obviously such areas act as reservoirs in which are accumulated numerous remnants of preceding faunae, some capable of further expansion under the proper conditions, others not.

In summary, faunistic evolution appears to be a diphasic phenomenon correlated with a diphasic climatic cycle. One phase, of *Dispersal,* alternates with another phase, of *Regression,* in which extinction, survival near mountains, differentiation, or southward migration into new territory is the rule.

Inasmuch as simple climatic cycles are apparently part of a still greater cycle, so also, presumably and apparently, simple faunistic cycles are part of still greater cycles, the major ones of which have been designated in the Americas as the North American, Old Northern and South American.

Furthermore, it is suggested that mountain masses serve as the most important (primary) centers of dispersal of animals; the more venerable and the more extensive the range, the greater its importance. It is not implied, however, that areas of other topography cannot serve as secondary and lesser centers of dispersal; they

obviously can and do. The point here is simply that mountains, because of their longevity and wide range of environmental inducement, can and do play a more important part than other areas can do.

The plateaus of Mexico and Guatemala are admirably formed and situated to act as dispersal centers of the greatest importance. They are ancient, dating from the Cretaceous. They are extensive and varied, offering an enormous variety of habitats for infiltration. They are easily accessible by coastwise pathways. They are at or near the termination of a cul-de-sac into which migrated a succession of forms dispersed from other areas and retreating southward. And they are so placed latitudinally that they offer a wide vertical range of climatic zones, from tropical to subarctic.

The minutiae of the operation and interaction of the three chief phenomena associated with herpetogeny in the area treated cannot be discussed here. The importance of various secondary portals, however, especially the Tehuantepec portal, deserves special emphasis. Several papers (Bogert and Oliver, 1945; Mittleman, 1942; Stuart, 1941; Smith and Laufe, 1946) treat these details, and numerous other studies on phylogeny bear out the general features mentioned herein.

III. PRESENT FACIES OF DISTRIBUTION

Simpson (1943) has emphasized that, historically, all of Central America is more closely allied with North America than with South America, despite the fact that the modern faunae of the first and last hold much in common. For that reason, and others, use of the terms Neotropical and Nearctic in the classical sense, to denote major zoogeographic areas, is frowned upon. Simpson suggests as more in keeping with the facts 5 areas: (1) Boreal North America, (2) Middle North America, (3) Southern North America, (4) Equatorial South America, and (5) Austral South America.

These 5 areas have received little comment. Mayr (1946) does not adopt them. For my own part, I do not see that the concepts involved in the classical zoogeographic divisions conflict with the horofaunal concept. True it is that any zoogeographer must analyze the history of the fauna of his area. Equally true is it that we still need boundaries in the terms of modern geography. The animals are not now distributed as they were millions of years ago. Naturally distinct areas possess their own peculiar faunae at the present time as surely as did like areas in past eras. Obviously any area is to be characterized by the proportion of one horofauna as compared with another. That does not mean its fauna must be exclusively of one horofauna. At no time, it must be remembered, have the major horofauna been zoogeographically distinctive since the Miocene. To attempt to superimpose midtertiary zoogeography on modern zoogeography is utter futility. To use midtertiary zoogeographic facts to arrive at an understanding of modern zoogeographic phenomena is undeniably desirable.

The basic unit of zoogeographic divisions of any time, present or past, is the biotic province; these in turn may be considered collectively in groups as sub-regions; the subregions in groups known as regions. As surely as the biotic province is a

valid concept in itself, the classical concept of the zoogeographic region is valid. That they should closely conform with gross physiographic features such as continental outlines is no more that reasonable; each of the lesser units in turn conform with lesser physiographic features.

In theory, I see no reason to discard the commonly accepted idea of the zoogeographic regions known as the Nearctic and Neotropical. Likewise there is little gain at the present time in substituting Simpson's 5 areas, inasmuch as these are far from adequately defined. In fact, however, there is much to debate regarding the exact position of the common Nearctic-Neotropical boundary. That line cannot be established until the distribution of all groups is known. Even then, if a given balance between the several horofaunae and their divisions is the ultimate criterion, very likely the boundary will vary in position according to the group considered. A compromise will ultimately be necessary. At the present time I follow the evidence generally accepted among herpetologists in allocating this boundary.

It is not the purpose of the present paper to discuss the relative merits of the several schemes of classification of the biotic provinces of Mexico. A number of recent contributions have discussed the subject in detail (Bogert and Oliver, 1945; Burt, 1938; Goldman and Moore, 1945; Smith, 1940; Van Rossem, 1945; see also Bancroft, 1926), although only two of these have been based upon the herpetofauna (Bogert and Oliver; Smith). A fair degree of correlation exists between all of these proposals, although the animal groups concerned have differed.

In Guatemala only one attempt has been made to distinguish biotic provinces (Stuart, 1943). This was based chiefly upon salamander distribution.

Despite lack of uniformity in categorization, a sufficient agreement between all schemes exists, at certain levels, to confirm the existence in nature of distinct biotic areas in Mexico and Central America. They are sufficiently distinct that wide-ranging species can, more often than not, be expected to possess variations closely correlated geographically with the general limits of the provinces. One can be fairly confident, for example, that Tamaulipan animals, regardless of kind, are going to be significantly different from Tabascan animals, although the difference may be either lesser or greater than subspecific rank. That any attempt to delimit such natural areas, however ephemeral they may be in the geological scale, is a step forward in the understanding of animal distribution is unquestionable.

The theory of biotic provinces is approved by perhaps most zoogeographers, but practice of the theory is greatly hindered by an almost universal lack of agreement upon the magnitude of subdivision (based upon percentage of forms influenced by it) implied by the biotic province. The various subdivisions of the major regions suggested are obviously not directly comparable, and the differences that exist in boundary locations are largely due to a different weighting relative to each other of various possible choices of boundaries, not so much in failure of agreement that the various boundaries exist.

It is true that this lack of agreement is partly due to extremely inadequate distributional data from sizeable areas. Yet complete data would not in themselves

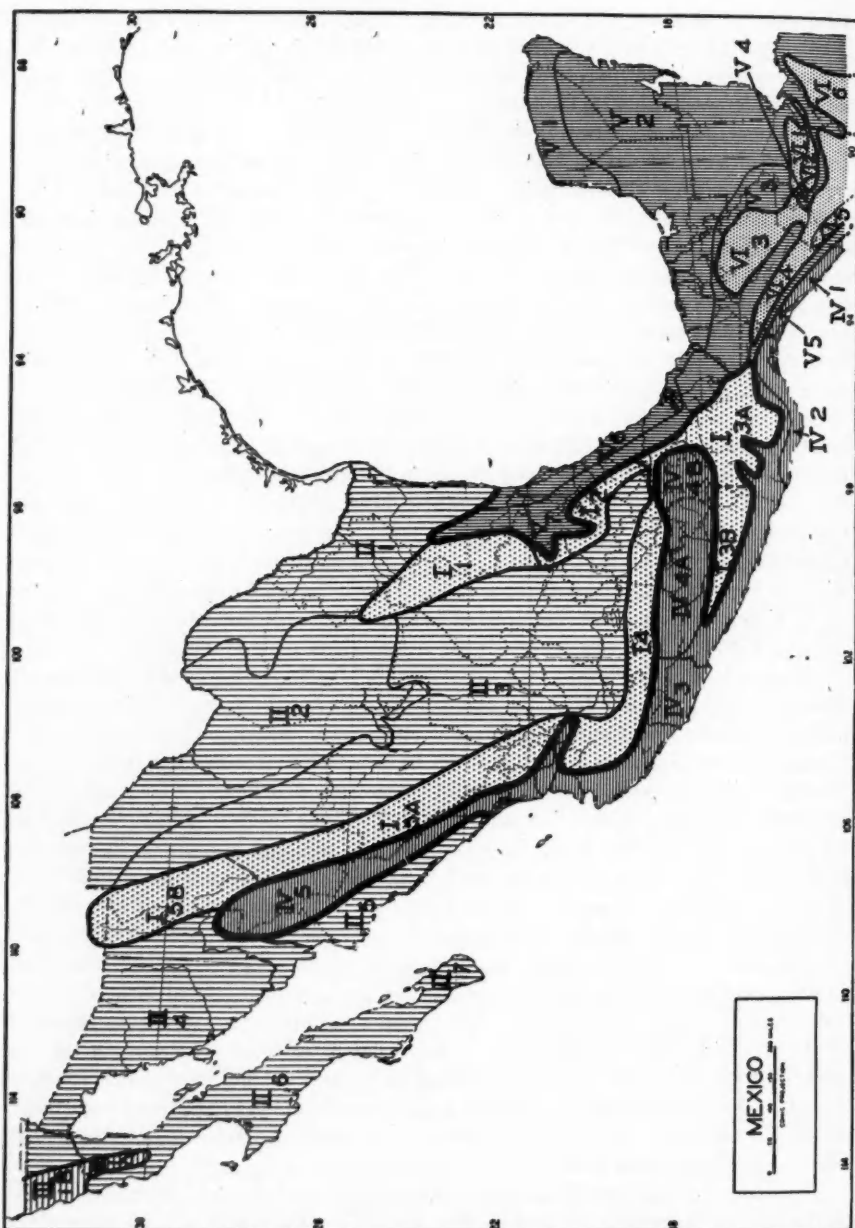FIG. 1. The biotic subdivisions of Mexico. The heaviest line indicates the Nearctic-Neo-tropical boundary. Lines of medium weight indicate boundaries between subregions; fine lines border the provinces, and dashed lines the districts. Each of the 6 types of shading is restricted to a single subregion; likewise all provinces of a given subregion bear the same Roman numeral. See text for explanation of letter and numerical symbols.

suffice, for no two cases are to be expected to duplicate each other.

Standardization of biotic areas would be extremely difficult by precise boundary analysis on the basis of amount of change in fauna per given linear unit (as for instance 1 kilometer). A more reasonable method of standardization would be the arbitrary establishment of limits of faunistic distinctiveness for various subdivisions —including biotic provinces—of major regions. Once such limits are established, authoritative delimitation of biotic areas on the basis of one part of the fauna should be relatively simple. What is needed is a rule by which new situations may be measured and some uniformity maintained.

Formulation of such a rule is certainly not the work for any one man. The scheme, if it is to be effective, must be assured of wide approval in advance of proposal. Nevertheless certain truths are self-evident:

1. A sample area must be selected for study. Inasmuch as California and adjacent areas are perhaps the most intensively collected and studied in the Americas, that is most reasonably the region to be selected.

2. Inasmuch as future students cannot well analyze an entire fauna at one time (no more than in the past), nor will always be able to analyze an officially designated "index" group, it is suggested that indices be formulated for each of the following three groups of terrestrial vertebrates: (a) reptiles and amphibians, (b) mammals, and (c) birds. A total-fauna index possibly could be established later, when feasible.

It is suggested that the Ecological Society of America, as the organization most intimately concerned with this problem, appoint a committee on biotic provinces whose duties are to include an analysis of the distribution of Californian terrestrial vertebrates and to propose, on the basis of such study, a separate index for establishment of biotic areas by percentage distinctiveness of each of the herpesian, avian, and mammalian faunae.

Prior to the completion of such a long-range program, I believe it is possible to group the Mexican provinces into assemblages which are more certainly of obviously close interrelationship and of mutual distinctiveness than the lesser areas suggested. They are as follows:

Nearctic Region
    I. Sierran Subregion
        1. Austro-oriental Province
        2. Hidalgan Province
        3. Sierras del Sur Province
           a. Oaxacan District
        b. Guerreran District
        4. Austro-occidental Province
        5. Yaquian Province
           a. Durangan District
           b. Apachian District

II. Sonoran Subregion
  1. Tamaulipan Province
  2. Mapimí Province
  3. Austrocentral Province
  4. Arizonan Province
  5. Sinaloan Province
  6. Peninsular Province
      a. Vizcaino Desert
      b. Southern Baja California
  7. Cape Province
III. Californian Subregion
  1. San Diegan Province
      a. Mártir District
      b. San Diegan District
Neotropical Region
IV. Pacific Subregion
  1. Tapachulan Province
  2. Tehuantepecan Province
  3. Acapulcan Province
  4. Balsan Province
  5. Fuerte Province
V. Atlantic Subregion
  1. Yucatecan Province
  2. Petén Province
  3. Palenque Province
  4. Zacapan Province
  5. Esperanzan
  6. Veracruzian Province
  7. Córdoban Province
VI. Guatemalan Subregion
  1. Quecchian Province
  2. Sierran Province
  3. Cuchumatan Province
  4. Chimaltenangan Province
  5. Fuegan Province
  6. Merendon Province

Unquestionably many more districts, subdistricts, etc., should be recognized in a complete scheme of classification of the biotic areas of Mexico. Those mentioned here are only a few of the more conspicuous.

Unfortunately the names to be chosen for the provinces are unavoidable sources of disagreement. Names already in use have been adopted in the preceding scheme, whenever past usage is sufficiently similar to the present, to prevent ambiguity and confusion. In some cases it has been necessary to coin new names.

In the present scheme the most fundamental novelty is the segregation of the humid zone of lush vegetation and high temperatures between the semiarid coast and the high boreal zone. Allocation of this zone, where it exists as described, with the Nearctic Region is obviously preposterous; no one has so suggested. Yet faunistically it is so extremely distinctive from other areas included in the Nearctic Region that failure to segregate it is, I believe, an error of major proportion. It occurs as described along the entire Atlantic exposure, but on the Pacific only in Chiapas and Oaxaca. From Guerrero north to Sinaloa this zone reaches the coast; there is no flat coastal zone with a distinctive fauna. In Sinaloa northward to Sonora, as in Chiapas and on the Atlantic coast, the zone again extends inward along the western face of the escarpment, which is a considerable distance inland. This upland, humid tropical zone is not, of course, of uniform faunal composition throughout its extent, but even belongs in two major assemblages (subregions: Atlantic and Pacific). Heretofore this zone has been a source of divergence of opinion and of vacillation in boundary allocation; its segregation greatly clarifies an understanding of Mexican provinces.

Recognition of an additional set of provinces (4) within the limits of one or a set of life zones presents a question regarding the concept held for biotic areas as here outlined. The areas actually have been conceived within the limits of Dice's (1943) definition. They are continuous geographic areas possessing a fauna distinguishable to a certain degree from those of all adjacent areas.

The Life zone is a concept fundamental to both the biome and to the biotic area. Life zones are, of course, geographically discontinuous. So may biomes also be, but not, with perhaps rare exceptions, biotic areas. Biomes are, in effect, *horizontal* (not vertical) assemblages of life zones or of lesser zones within life zones. Biotic areas are, in general, *vertical* assemblages (never or rarely horizontal, combining isolated areas) or life zones.

Nevertheless biotic areas do not and cannot be conceived to be of equivalent vertical range in all areas. I present this suggestion as a theory: *the greater the continuous horizontal range of a life zone or set of life zones, the lesser the vertical range of the biotic area.* Areas broken up into small, discontinuous vertical assemblages of life zones, as in Guatemala, are divided into biotic areas of extremely great vertical range—i.e., entire mountain ranges from perhaps a few hundred feet above sea level to 10,000 or more feet. Large mountain masses and plateaus, however, extending over hundreds of miles, cannot be similarly treated, for obvious reasons. The only logical basis for division into biotic areas is to restrict the vertical range. Thus boundaries of biotic areas under such conditions will coincide with the boundaries of certain life zones. Such coincidence does not mean a breakdown in distinctness of the concepts of life zones and biotic areas. The forms (species, subspecies) within one biotic area still remain to a certain degree distinctive, in each and every zone within that area, from the forms of the zones (comparable or not) of adjacent areas. This is, indeed, the fundamental difference of a biotic area from a life zone.

In the following notes, comparisons are made chiefly between Goldman and Moore's provinces and those of Smith; for Guatemala and Chiapas, Stuart is also referred to. Essential agreement of the several authors with the arrangement here given is assumed if no direct reference to any of these papers is made. Dice's important survey has not been overlooked, but I regard it as superseded, for Mexico, by Goldman and Moore's work; in fact, there is an extremely close agreement between the two except in names.

I. Sierran Subregion. No name has been proposed for this distinctive area, which coincides with the high mountains lying about the periphery of the plateau. Moore's "Transverse Volcanic" province is the nearest approach in proposed areas and names, but that area does not include the Sierra Madre del Sur nor the northern Sierra Occidental and Sierra Oriental. Moreover I am not in agreement with the naturalness of the northern central limit of the boundary of the "Transverse Volcanic," inasmuch as the high, dissected plateau in Guanajuato, Querétaro and northern Jalisco show a much greater affinity zoogeographically and topographically with the dry central basin of the plateau than with the high, forested, periphery.

I 1. Austro-oriental Province. This coincides rather precisely with Goldman and Moore's "Sierra Madre Oriental" Province.

I 2. Hidalgan Province. The eastern part of Moore's "Transverse Volcanic." It is separated by the central basin from all other parts of the Subregion save those toward the South. Faunistically its relation is toward the west, *via* the chain of mountains in Distrito Federal, western Puebla, etc., but the fauna is quite distinctive. Although topographically it is closely correlated with the Sierras del sur Province, actually there is less faunistic relation than with the Austro-occidental Province.

I 3. Sierras del Sur Province. This is Goldman and Moore's "Sierra Madre del Sur" Province. It is essentially their name that is adopted here. Smith segregated a "Oaxaca Highlands" Province, and even placed it in a different region, but I now believe in error. This province, as others of the Sierran Subregion, is limited to high ridges and high plains. The coffee zone, which borders this province to the south, is not included.

I 3a. Oaxacan District. This is a subdivision of obvious distinctiveness. Oaxacan specimens often differ from Guerreran material.

I 3b. Guerreran District. Smith termed the whole Sierras del Sur Province the "Guerreran" Province. The term is here limited to the portion of the province in Guerrero.

I 4. Austro-occidental Province. This is the western part of Moore's "Transverse Volcanic." The fauna is very distinct from that of the area here called the Hidalgan Province, and from that of Guanajuato and adjacent areas, all of which are included by Moore in the Transverse Volcanic. The Austro-occidental Province is a forested area of rugged topography and high elevation (about 4500 ft. and higher, above sea level). The area to the north of this zone is grassland, chiefly level plains, with scattered mountains. Perhaps a chief cause for discrepancy between the present views of Moore and Smith is that Moore believes the montane

fauna is the more characteristic of the area, while I believe the same of the plains fauna. The preponderance of species to be considered is, in this area, and herpetologically speaking, the plains fauna.

I 5. Yaquian Province. This is Goldman and Moore's "Sierra Madre Occidental" Province, and Smith's combined Apachian and Durangan Provinces. The latter is undoubtedly too fine a division for the present category of Province, although the division is a natural one and is retained for Districts of the same name as Smith's Provinces. I have hesitated to adopt Goldman and Moore's name for the same reason that Austro-oriental was chosen over their "Sierra Madre Oriental" Province: the Sierra in both cases is more extensive than the Province, while the names actually chosen have no geographic limitations.

I 5a. Durangan District.

I 5b. Apachian District.

II. Sonoran Subregion. No term proposed in the past has carried exactly the meaning here intended. Perhaps the closest approach is the "Sonoran" region of Merriman and others. Its usage here, because of ambiguity, may be ill-advised.

II 1. Tamaulipan Province. Virtually all authors are agreed upon this province. Its western boundary was placed farther west by Goldman and Moore than by Smith, following the valleys of the larger tributaries of the Rio Grande. I believe they are correct, and have extended the boundary of the province westward accordingly. The southern boundary remains rather vague. I do not, however, approve of its extreme southern extension, as by Goldman and Moore, into Hidalgo and San Luis Potosí, which areas I would include, because of their tropical fauna and humid, hot climate, in the Atlantic Subregion.

II 2. Mapimí Province. This is characterized by low, semi-arid, largely undissected plains with scattered mountain ranges. It is very abruptly differentiated in the southeast from the Austrocentral Province by a high escarpment marking the northern edge of the main Mexican plateau. There is a great faunistic divergence of the two levels. In the west a dissected, high grass plain (Proplateau Province) blends rather gradually with the semi-arid lowlands of the Chihuahuan Province. In the southwest the plateau is deeply dissected and the numerous arid valleys, continuous with the Mapimí balsan, have somewhat distinctive faunae. These valleys rise rapidly toward their origins and rapidly transform in character to that of the Austrocentral Province.

The name is based upon that of the huge desert basin, the bolson of Mapimí, which covers most of the Province and, with its many extensions, in reality is coincident with the Province. I have rejected the name Chihuahuan because of its ambiguity, since that name has been used to denote areas of different extent, and because the city of Chihuahua actually lies within the boundaries of the Austrocentral Province. As a matter of fact, most of the state of Chihuahua lies in Provinces other than the one here termed the Mapimí, and to none of the 4 Provinces involved is the name "Chihuahuan" clearly applicable.

II 3. Austrocentral Province. This province corresponds most closely with

Smith's Province given the same name, but Goldman and Moore include this area in two Provinces: the "Chihuahua-Zacatecas" and the "Transverse Volcanic." As stated before, I do not at present agree that the northern boundary of the "Transverse Volcanic" is properly placed: I would push it farther south (to the northern border of the present Austro-occidental). Thus enlarged, their "Chihuahua-Zacatecas" Province coincides very well with the combined present Mapimí and Austro-central Provinces. In the discussion of the former I have emphasized the topographic and faunal distinctiveness of the Mapimí Province. Most debatable is the extension of the Austrocentral Province northward between the Mapimí and Yaquian Provinces. There is, however, a close relation between the high grass plains of Chihuahua—on which the city of Chihuahua is located—and the similar areas of the central plateau. The two are in reality one in topography, and essentially also in fauna. Inclusion of the area in Chihuahua with the Austrocentral zone clarifies greatly the confused picture of the western biotic areas.

The Austrocentral Province, with an enormous North-South extent, possesses a large number of lesser subdivisions, which cannot now be even superficially delimited. Numerous distinctive areas do exist, however, and their study is one of the most intriguing problems offered in the study of biotic areas of Mexico.

II 4. Arizonan Province. This is the same as Goldman and Moore's "Sonoran" Province, but their name is not, I believe, the best in view of its extremely wide usage. As a matter of fact, in the present arrangement the term has been used in a much broader sense. The name Arizonan, while perhaps not the best possible choice, is at least preferable as having a more limited implication.

II 5. Sinaloan Province. The southern extension of the Arizonan Province is obviously along the coast, not along the mountains, where in reality the Neotropical forms have migrated northward. The Arizonan fauna is a semi-arid one, the Neotropical (in this area), one of a humid, hot climate. This fact and the corresponding necessity in depiction of biotic provinces was not fully appreciated either by Smith or by Goldman and Moore.

Adoption of the term Sinaloan, with the revised concept of the Province, may be unwise. It is still quite appropriate, however, and in the absence of a readily evident suitable alternate is here retained.

II 6. Peninsular Province. Herpetological evidence strongly supports segregation of only two *major* Provinces in Baja California: the Cape Province, and the remainder for which the term Peninsular of Smith may be retained.

II 6a. Vizcaino Desert District.

II 6b. Southern Baja California District.

II 7. Cape Province. It is obvious that, overlooking the degree of distinctiveness, the Cape of Baja California *does* have a distinctive fauna. Herpetologically, it is the most distinctive of the entire Peninsula. I can see no alternative to recognition of it as a separate Province. The rest of the Peninsula, exclusive of the Californian Subregion, does not possess distinctive enough a division to parallel that of the Cape, and therefore I see no alternative to recognition of the remainder as one Province,

the Peninsular.   I do readily agree that a lesser subdivision corresponding with that between Goldman and Moore's "Vizcaino Desert" and "Southern Baja California" Provinces is warranted.   These I would make Districts, but the latter of course does exclude the Cape area.

III.   California Subregion.   This has been accepted by all zoogeographers, without exception.

III 1.   San Diegan Province.   While there is no question that the San Pedro Mártir area is faunistically distinctive, I cannot see that it is distinctive to the degree that are other provinces of Baja California.   I would consider it a district, equivalent to the San Diegan district.   The two together may be regarded as constituting the San Diegan Province.   This province may well include other districts in the United States.

IV.   Pacific Subregion.   This is a new name for virtually the entire group of Provinces on the Pacific coast, west and south of the Sierran provinces.   They appear to be naturally interrelated.

IV 1.   Tapachulan Province.   This is the coastal zone, possibly coincident in part with Stuart's "Escuintlan" Province, and certainly in part with Goldman and Moore's "Tehuantepec" Province.   I see little relationship, at this level, between the faunae of this coastal area and of the main Tehuantepec area.   Likewise distinct in fact is the "coffee" zone inland from the Tapachulan Province.   This shows a strong and remarkable relation to the Atlantic Subregion, where it is here placed.

The name Tapachulan is somewhat inappropriate, inasmuch as that city, and most others on the coast, is situated on the boundary between the coastal zone and the "foothill" humid zone.

IV 2.   Tehuantepecan Province.   This includes the vast arid and semi-arid flats such as that where the city of Tehuantepec is located.   A humid coffee zone of very distinctive fauna is present about the southern edge of the mountains, and should not be confused with the more xeric fauna of the lowlands.

IV 3.   Acapulcan Province.   A humid, hot climate is characteristic of this province.   It skirts the southern edge of the Oaxaca Sierras, not there reaching the coast, but elsewhere it reaches the coast, with minor gaps, to its northern border near Mazatlán.   It is a remarkable and definite fact that on the Pacific coast west of the Isthmus of Tehuantepec except for certain valleys, there is but one major zone or Province from the edge of the Sierran Provinces to the coast, but on the Atlantic and Chiapas coast there are two.

This province is virtually the same as Smith's "Lower Balsan" and Goldman and Moore's "Nayarit-Guerrero" Provinces, with the exception of the Balsas Valley. Inasmuch as that Valley is an extremely arid basin with a very distinctive fauna it is impossible to place the two together.

IV 4.   Balsan Province.   The vast valley system of the Rio Balsas and its tributaries is arid or semi-arid throughout virtually its entire extent, and furnishes some of the most scenic splendor of Mexico.   It is extremely distinctive in fauna from other areas, but curiously enough meets the Austrocentral Province in the

upper part of the valley, where little topographic distinction between the two exists.

The upper part of the valley could well merit distinction as a district. It was regarded as a full province by Smith, but I now believe in error.

IV 5. Fuerte Province. The faunistic affinities of the area here denoted as the Fuerte Province are distinctly southern, as is also the climate. A split such as this seems essential, in both Smith's and Goldman and Moore's "Sinaloan" Province, to convey this fact. Both to the west (the present Sinaloan Province) and to the east (Yaquian Province) the fauna is clearly of northern derivation.

This name is based upon one of the main rivers, the Rio Fuerte, draining the Province, and whose upper valley forms a large and perhaps the best-known part of the Province.

V. Atlantic Subregion. This is one of the largest of the subregions here recognized, and is one of the most complex in outline. It includes the lowland coastal areas and the upland, humid zone just below the level of the Sierran and Guatemalan Subregions. One of its most curious features is the extension of one of its Provinces (here called the Esperanzan) onto Pacific exposures. A very large variety of species verify the actual existence of this configuration.

V 1. Yucatecan Province. The northern end of the Yucatán Peninsula possesses a fauna distinctive from that to the south. It is correlated with a rather dry climate, shallow soil and low vegetation. To the south the rainfall is heavier, the soil deep, the vegetation high. There is little difference between the forests of Chichén Itzá, for example, and Campeche, but there is a big difference between Chichén Itzá and Mérida floristically *and* faunistically. Goldman and Moore do not recognize the province, although Smith does.

V 2. Petén Province. A flat, monotonous plain, much of it under water in the rainy season, consisting both of forest and of savanna, but all with a pretty homogenous fauna. Brodkorb has shown the distinctness of a "Tabascan" District. In Guatemala the boundaries have been worked out by Stuart, whose conclusions are here adopted without alteration. Goldman and Moore apparently have much the same concept of the area as here given, but include less of Guatemala, all of the Yucatán Peninsula, and exclude the portion Brodkorb recognizes as the Tabascan District. In fact his western boundary of the Tabascan District (and the boundary here taken as the western edge of the Petén Province) is not recognized at all by Goldman and Moore. In fact I believe this boundary more important than the one they use the western limit of their "Yucatan Peninsula" Province (and which Brodkorb uses as the eastern edge of the Tabascan District).

In the present scheme the humid foothills as in the immediate vicinity of Tenosique, around Piedras Negras, and around the ruins of Palenque (not the present town of Palenque) are typical of another Province (the Palenque Province) of remarkably distinct fauna. This has been rather slighted in the past, placed with the Petén Province or with the plateau provinces of Chiapas.

V 3. Palenque Province. A rather extensive area, in which are situated the

ruins of Palenque, following the central valley of Chiapas into Guatemala, and across the Isthmus of Tehuantepec into southern Veracruz.

V 4. Zacapan Province. Two isolated, arid valleys in Guatemala, on the Montagua and Negro rivers, are regarded by Stuart as distinct from other areas and related to each other.

V 5. Esperanzan Province. The humid coffee belt on the Pacific slopes of Chiapas is, as has long been known, related to the same belt in Veracruz. It is nevertheless distinctive in its own right. The name is taken from a finca, La Esperanza, which lies on the very edge of this belt and where most of the exploration of the Province has been done.

V 6. Veracruzian Province. This is a flat coastal belt of grassland and scattered trees which has little in common with the forested foothills included here in the Córdoban Province. It extends from about the Coatzacoalcos River on the south to southern Tamaulipas in the north. The northern boundary is not abrupt and cannot now be accurately placed. It may include even extreme northern Veracruz.

V 7. Córdoban Province. The city of Córdoba, Veracruz, lies well within this Province, perhaps the richest faunistically in all Mexico. To the north it extends along the low hills inland, for example, from Cuidad Victoria. It penetrates the states of Hidalgo and San Luis Potosí in the valleys of the Panuco River System. This northern part is placed by Goldman and Moore in the Tamaulipan Province, but the reptiles and amphibians, while showing some Tamaulipan influence in that area, include so many typically tropical genera that the allocation here made seems much more reasonable.

VI. Guatemalan Subregion. This is an area of high elevation, very comparable to the Sierran Subregion of Mexico. In Mexico it has been regarded as including but one province, called the "Chiapas Plateau" by Smith, "Chiapas Highlands" by Goldman and Moore. Stuart has studied the adjacent area in Guatemala intensively and shows clearly the need for subdivision.

VI 1. Quecchian Province. The Alta Verapaz highlands.

VI 2. Sierran Province. The Sierra de las Minas, Sierra de Chuacús and Sierra de los Micos, south of Alta Verapaz.

VI 3. Cuchumatán Province. The large northern Chiapas highlands, continuous in Guatemala with the Cuchumatán Sierra.

VI 4. Chimaltenangan Province. The southern portion of the Chiapas highlands and the northern face of the central Guatemalan plateau.

VI 5. Fuegan Province. The high volcanic ridge from Tacaná on the Mexican border through Guatemala.

VI 6. Merendon Province. The mountain ridge adjoining Guatemala and extending probably through much of Honduras.

Undoubtedly the divisions as arranged in the preceding are not uniformly comparable. At least the assemblage of them in natural units of larger size is a forward step. So also, I believe, is the more accurate segregation of lesser units. Shifting of these units up or down the scale of graded biotic areas, and splitting still further,

is to be expected as the fauna becomes better known and the actual distribution better indicated. Important as such progress is, however, none of it will be stable until some such an index of biotic areas is established as previously suggested.

SUMMARY

1. No assistance in analysis of herpetogeny in Mexico and Guatemala is afforded by fossil records in those countries.

2. The Mexican and Guatemalan plateaux are populated preponderantly by primitive species, chiefly of the Old Northern horofauna.

3. The herpesian rate of differentiation is slower than the mammalian.

4. Three major horofaunae are discernible in the Western Hemisphere: a pre-Miocene South American and Old Northern, and a post-Oligocene North American. A post-Pliocene subdivision of the latter is the Holarctic.

5. Late Oligocene or early Miocene is suggested as the most probable time that the Panamanian oceanic portal was closed.

6. Development of a fauna (faunogeny) is accomplished by a succession of *Dispersal* phases alternating with *Regression* phases; three major cycles occurred in the Americas, as indicated in paragraph No. 4. Many lesser cycles occurred. In either phase of faunogeny, but especially the Regression phase, three phenomena are in operation that contribute to preservation and divergence of the fauna:

    a. The *Cul-de-Sac Phenomenon*, by which forms are preserved by southward migration into new territory.

    b. *Isolation Phenomenon*, by which forms are preserved and permitted to differentiate in isolation.

    c. *Montane Phenomenon*, by which forms are preserved by ebb and flow on mountain slopes in favorable areas.

7. Mountain masses play an important role in both phases of faunogeny, serving as primary centers of dispersal and primary centers of refuge.

8. Mexico and Guatemala are regarded, collectively, as primary (hemispherically speaking) or secondary (globally speaking) centers of dispersal; separately as tertiary centers.

9. Infiltration of southern North America by the South American group is a function of distance from the southern center of dispersal, in spite of the fact that certain groups obviously progressed farther than others. The total contribution steadily diminishes centrifugally.

10. The sequence of zoogeographic divisions is from the lesser to the greater: district, province, subregion, region.

11. The commonly accepted zoogeographic regions of the Western Hemisphere —the Nearctic and Neotropical—are acceptable neo-zoogeographic divisions. They are reasonably accurate expressions of present day faunal patterns, although an understanding of those patterns, peculiar as they are, requires knowledge of paleozoogeography.

12. Standardization of faunistic limits of biotic areas should be based upon

percentage distinctiveness of the fauna.

13. Such standardization should be based upon study of a well-known sample area, California and environs recommended. It should include indices for each of the terrestrial vertebrate faunae: herpesian, mammalian, avian.

14. Thirty-one biotic provinces in Mexico and Guatemala are grouped into six subregions: Sierran (5 provinces), Sonoran (7 provinces), Californian (1 province), Pacific (5 provinces), Atlantic (7 provinces), and Guatemalan (6 provinces).

15. A set of biotic provinces (four) is added to the series previously proposed, corresponding with the humid zone of lush vegetation near the coasts.

16. Use of certain life zone boundaries as boundaries between biotic areas does not imply a breakdown in distinctness of concepts of life zones and biotic areas.

17. The life zones concept is fundamental to both the biome and biotic area concepts.

18. Biomes are horizontal assemblages of either geographically continuous or discontinuous life zones or vertical parts thereof.

19. Biotic areas are vertical assemblages of geographically continuous but faunistically distinctive portions of life zones.

20. Within any given major area, *the greater the continuous horizontal range of a life zone or set of life zones, the lesser the vertical range of the biotic area.*

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